Technological Innovation Systems: The case of hydrogen from waste

Actor characterisation using Q methodology and three case study investigations of regional technological innovation systems using novel interaction matrices.

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Abstract

This thesis addresses regional aspects of the technological field of hydrogen production from waste. It develops the characterisation of experts involved in the innovation of hydrogen from waste technologies through the use of Q methodology; and a new model (IM-TIS) for the analysis of technological innovation systems.

The literature review revealed that the sustainable production of hydrogen from waste processes was not well represented. Truffer *et al*. (2012) identified a need to further investigate the relationships between functions of innovation and how a technological innovation system may change over time. This was reflected in other innovation and transitions literature.

Q methodology revealed three different group identities associated with actors involved in the technological innovation system for hydrogen from waste. These identities are, Hydrogen from Waste Advocates, Cautionary Environmentalists and Hydrogen Technologists.

The IM-TIS model developed for this research was applied to three case study regions in the field of hydrogen production from waste in the UK. The model is an adaptation of two existing conceptual models, Rock Engineering Systems (RES) and Functions of Innovation.

The thesis identifies and reports on the characteristics of groups of experts involved in hydrogen production from waste and their potential importance. The application of IM-TIS to the three regional case studies of Tees Valley, London and South Wales is presented. A further application of the IM-TIS model using pathway analysis is applied to the case study region of London and results are presented in a worked example.

This is the first time a model of this type has been applied to technological innovation system case studies in the UK. It is also the first time a variation of the RES model has been applied in the ways presented in this thesis. The new model provides the opportunity to examine the relationships between functions of innovation and identify what may change within the system over time.

It is concluded that the IM-TIS model offers an analysis tool for technological innovation systems that can incorporate the relationships and interactions that occur within the system in a non-linear fashion. Evidence from the research suggests that these interactions have not been adequately addressed in previous studies. A further conclusion is that by addressing the production of hydrogen from waste using these methods, hydrogen technologies are shown to be still in an emergent state.

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I would also like to say a special thank you to the South Wales roller derby community, CRoC, Tiger Bay Brawlers, South Wales Silures and Dare Valley Vixens for giving me an outlet, knocking me down and picking me up again.

DEDICATION

For my Parents: John and Carol

Thank you for always being supportive. Here it is, the last phase of the infamous 19 year long 10 year plan. I hope you like it.

With love and affection.

"The more things that you read, the more things you will know, the more things that you learn the more places you'll go"

Dr Seuss

"Guess what? You're not tired"

Chalene Johnson (Beachbody Fitness Instructor)

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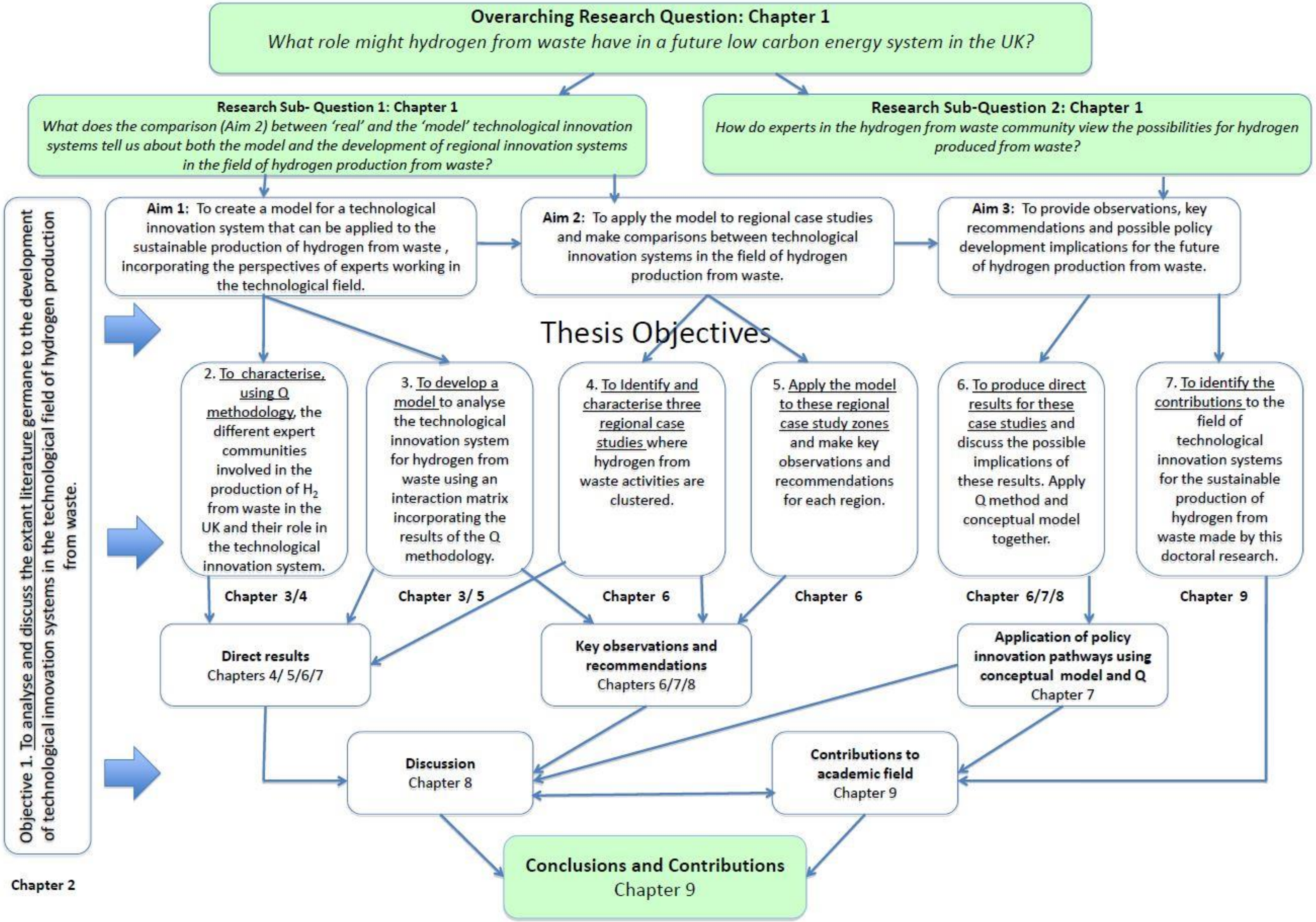
GLOSSARY OF TERMS

AD	Anaerobic Digestion
AIS	Agricultural Innovation System
AISA	Agricultural Innovation System Azerbaijan
C&I	Commercial and Industrial
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CoV	Coefficient of Vulnerability
CTA	Constructive Technology Assessment
DECC	Department for Energy and Climate Change UK
DEFRA	Department for Environment, Food and Rural Affairs UK
DOENI	Department of the Environment Northern Ireland
EC	European Commission
EfW	Energy from waste
EIA	Environmental Impact Assessment
EU	European Union
FoI	Functions of Innovation
GHG	Green House Gases
GIS	Geographical Information Systems
GLA	Greater London Authority
GVA	Gross Value Added
H_2	Hydrogen
H_2fW IM-TIS(LN)	IM-TIS Application Case Study London
H_2fW IM-TIS(SW)	IM-TIS Application Case Study South Wales
H_2fW IM-TIS(TV)	IM-TIS Application Case Study Tees Valley
HRT	Hydraulic retention time
IoE	Indicators of Effectiveness
IPCC	Intergovernmental Panel on Climate Change
KTN	Knowledge Transfer Network

MLP	Multi Level Perspective
MSW	Municipal Solid Waste
NGO	Non-Governmental Organisation
OECD	Oganisation for economic co-operation and development
PTA	Participatory Technology Assessment
Q sort	Q methodology statements
RES	Rock Engineering Systems
IM-TIS	Interaction Matrix – Technological Innovation Systems model
r_{xy}	Pearson's r correlation coefficient
TIS	Technological Innovation System
WG	Welsh Government
WTE	Waste to energy



RESEARCH FLOW DIAGRAM

1 Introduction

This thesis addresses the research question: *What role might hydrogen from waste play in a future low carbon energy system in the UK?* To this end, a mixed methods approach has been undertaken in which the methods used aim to acquire knowledge of the technological innovation system supporting the sustainable production of hydrogen from waste. This includes the individuals, organisations, actors and institutions involved in the system. The research investigates whether the drivers and barriers for deployment of hydrogen from waste technologies are changing with the growth in knowledge of climate change and technological developments. The hypothesis: *that the supporting drivers and barriers for the use of hydrogen as a fuel have not changed over the last twenty years despite the technological advancement in the field,* is presented.

Also under consideration, is whether achieving commercialisation of hydrogen from waste technologies can be improved or altered if approached from the perspective of the actors involved in the technological innovation system. Two further research sub-questions are considered to help address this:

1. *What does the comparison between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste? and*
2. *How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?*

The EPSRC SUPERGEN H Delivery Consortium, a consortium of fourteen universities focusing on the sustainable production of hydrogen, funded this multidisciplinary doctoral research. It was developed and undertaken in order to contribute to the academic fields addressing the growing UK concerns relating to the impact that fossil fuel emissions are having on the Earth's climate.

This chapter is structured as follows: Firstly, the rationale and policy relevance are presented, to contextualise the research and identify the importance of UK policies within the technological innovation system. This is followed by the research study's aims and objectives. Finally, the thesis layout is presented.

1.1 Hydrogen: policies, climate change and low carbon transitions

Hydrogen energy has been described as "a long term and highly uncertain option for enabling deep decarbonisation of the energy system" (McDowall 2012). Research over the past twenty years has been undertaken to consider the role that hydrogen might contribute to a future low carbon energy and transport system (McDowall & Eames 2006; Balat & Kirtay 2010).

1.1.1 Hydrogen production from waste: the climate change agenda

We are faced with a number of fundamental sustainability challenges presented in different domains. Energy supply is one of these challenges and is confronted by issues that include the depletion of natural resources, air pollution and greenhouse gases (GHGs); the uncertainties relate to both short and long term security of supply (Markard *et al.* 2012) and contributions to climate change. The Intergovernmental Panel on Climate Change (IPCC 2007; 2011) states that, without action to reduce emissions of GHGs, there is a significant probability that global average temperatures will increase to more than 2°C higher than in pre-industrial times, with substantial changes in regional climate and damaging consequences for human welfare and ecological systems, over the course of this century and beyond.

There is now a plethora of global agreements, national strategic documents and EU and UK laws that have addressed the climate change issue including, *inter alia*:

- The Kyoto Protocol (UNFCCC 1997)
- The European Climate Change Programme (EU 1991)
- The Revised Waste Framework Directive 2008 (EU Parliament 2008)
- UK Climate Change Act 2008 (UK Parliament 2008)

- The Low Carbon Transition Plan (HM Government 2009)
- The Carbon Plan (HM Government 2011)
- DECC Science and Innovation Strategy 2012 (DECC 2012)

These measures have been produced in order to encourage a reduction in global, national and regional emissions of GHGs, especially those caused by the burning of fossil fuels for energy and transport use. These emissions, often measured in terms of CO_2 equivalent, are widely accepted by the majority of the scientific community to be the primary contribution to anthropogenic climate change (IPCC 2007).

In the UK, Lord Stern was commissioned by the Treasury to investigate the economics, costs and risks of climate change (Stern 2006), which indicates that the UK Government was open to taking policy decisions informed by this review. Stern (2006) makes the connection between CO_2 and climate change with the following statement

> *"The current level or stock of greenhouse gases in the atmosphere is equivalent to around 430 parts per million (ppm) CO_2, compared with only 280ppm before the Industrial Revolution. These concentrations have already caused the world to warm by more than half a degree Celsius and will lead to at least a further half degree warming over the next few decades, because of the inertia in the climate system."*

CO_2 emissions are considered in this report to be fundamental in contributing to climate change. The review states that, since 1850, America and Europe have produced 70% of global CO_2 emissions. However, from the evidence in this review, it is expected that the majority of future emissions will come from developing countries due to the rapid growth in population and energy-intensive industries. In order to prevent catastrophic climate change, Stern (2006) suggests that stabilisation of CO_2 concentrations to any acceptable level will require an annual reduction in emissions that will allow for the Earth to effectively deal with GHGs; a reduction in CO_2 emissions of more than 80% below the absolute level of the current annual emissions was indicated.

The Stern Review led the way in encouraging the UK government to begin the think about and act on transitioning to a low carbon future. The UK Climate Change Act 2008

(UK Parliament 2008), produced after Stern (2006), sets legally binding targets for the reduction of GHG emissions in the UK, requiring that they be reduced by 80% of their 1990 levels by 2050 via a series of carbon budgets. The aim of the Act is to ensure that the UK contributes to reducing the predicted rise in temperature to an acceptable level and subsequently reduce possible damage to human and ecological systems (Shuckburgh *et al.* 2012).

In the UK, these concerns are combined with the desire to develop low carbon sustainable technologies that may also secure UK energy supplies into the future. The UK Government (DECC 2011) has a target to:

- Drive the deployment of renewable energy across the UK to ensure that at least 15% of UK energy comes from renewable sources by 2020.

This shows commitment from the UK Government to contribute to meeting the EU Renewable Energy Directive (European Parliament 2009) target of aiming to obtain 20% of Europe's energy from renewable sources by 2020.

The DECC Science and Innovation Strategy 2012 (DECC 2012) identifies ways to deliver secure energy on the way to a low carbon future in the UK. This is described as a "…larger, smarter grid, together with other elements of a new electricity system, such as smart meters, micro-generation of electricity by individuals and businesses, smart appliances and electric vehicles…. The development of a smart grid lies at the centre of this vision for a transformed low-carbon electricity system. It forms the backbone of the new system, and will need to be intelligent, flexible and responsive…." Based on DECC (2012)'s energy delivery identification, sustainably produced hydrogen could be considered to offer valuable potential in contributing to this new UK energy system. This could be as a storage medium to support intermittency problems found with other renewable energy sources, or as fuel to charge fuel cells for use in transportation or other purposes.

A more detailed policy landscape is described in detail in Chapter 2, Section 2.1. Three tiers of policy will be explained, beginning with the European Union (EU) legislation and roadmaps. The pathway from these to the UK national policies and strategies and their relationship to this research will be described. The third tier of policy and strategies is represented by the application of national policies through the devolved administrations of London and South Wales; these are described in Chapter 6 (Case Studies).

There are numerous legislative acts, policies and strategies which could have an influence on the sustainable production of hydrogen from waste. However, as we shall see, direct mention of hydrogen production from waste is uncommon in all government documents.

1.1.2 The role of innovation systems in low carbon transitions

Innovation systems, and how they function, have become an important consideration of technological assessment in terms of moving towards a low carbon economy (Negro *et al.* 2007; Negro *et al*. 2008; Suurs *et al.* 2010; Hawkey 2012; Breukers *et al.* 2013). Truffer *et al.* (2012) attribute the increasing attention to energy related innovation as a possible result of developments in policy discourses in many countries. The production of complementary innovation and environmental polices is recognised as a complex issue (Foxon & Pearson 2008). The development or greater understanding of a new or existing innovation system for a particular sector or technology may create an environment where the roles of actors and institutions are better understood. This may lead to sustainable technological innovation. Sustainable innovation is defined by Foxon & Pearson (2008) as: *"innovation towards more sustainable technological and institutional systems and processes—broadly understood as systems for which resource use and waste production remain within appropriate environmental limits and socially acceptable levels of economic prosperity and social justice are achieved."*

To address sustainable innovation, conceptual frameworks and models from the innovation systems literature provide a variety of different viewpoints and approaches. (Foxon *et al*. 2005) define an *innovation system* as "the elements and relationships which interact in the production, diffusion and use of new and economically useful knowledge"; this is the definition applied in this research. The term *national system of* *innovation* was first described by Christopher Freeman in his 1987 paper (Freeman 1987), a study of the Japanese economy in the 1980s. From that point, the literature has developed and evolved to include regional innovation systems, sectoral innovation systems, and then, in more recent years, the *functions of innovation* have been identified and described (Johnson 1998; Hekkert *et al*. 2007).

The need to develop an interconnected system to deliver innovations is often observed in innovation literature (Negro *et al.* 2007; Negro *et al*. 2008; Suurs *et al.* 2010; Hawkey 2012; Breukers *et al.* 2013;) this system should apply a structure to the field of innovation under investigation. The terms innovation system and, specifically, *technological innovation system* (TIS) are of particular interest to this research. A TIS is a form of sectoral innovation system that aims to address a particular technological problem. Its conception can be traced back to Carlsson & Stankiewicz (1991), who highlighted the systemic interplay of firms and other actors operating under a particular institutional infrastructure as the essential driver for the creation, utilisation and commercialisation of new technologies (Truffer *et al.* 2012).

In the context of this thesis, the technological field is the sustainable production of hydrogen from waste. What is contained within the system may depend on the technological field of innovation or the area of research under scrutiny. To gain further insight into the workings of innovation systems' drivers, barriers and system connections, the original TIS framework has seen a number of conceptual refinements (Truffer *et al.* 2012). Publications relating to the functions of innovation have emerged over the last decade (Johnson 1998; Hekkert *et al.* 2007; Bergek *et al.*2008). The 'functions of innovation' literature aims to identify the different activities that occur within the innovation system framework and are required to achieve successful innovation in a technological field.

As the literature review will show, however, current focus on technological innovation systems is often on the theory of innovation and the conceptual design of an innovation system rather than on the practical application of an interactive innovation system to an existing or emerging technology or technological process. The focus of the research in this thesis is on these practical aspects.

The following section sets out the aims and objectives of this research project, which are followed by a description of the thesis structure and chapter contents.

1.2 Study Aims and Objectives

This doctoral research was conducted between 2009 and 2013 and was funded by the EPSRC SUPERGEN XIV H-Delivery consortium, later renamed *Delivery of Sustainable Hydrogen*.

The research focuses on the role of technological innovation systems in the production of sustainable hydrogen from waste management activities. The research plan identifies the overarching research question: *What role might hydrogen produced from waste have in a future low carbon energy system in the UK?* together with two further sub-questions:

- *"What does the comparison (Aim 2) between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?"* and
- *How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?*

To address these research questions, three further aims for the research were identified:

1. To create a model of a technological innovation system that could be applied to the sustainable production of hydrogen from waste, incorporating the perspectives of experts working in the technological field.
2. To apply the model to regional case studies and make comparisons between 'real' and 'model' technological innovation systems in the field of hydrogen production from waste.

3. To provide observations, key recommendations and possible policy development implications for the future of hydrogen production from waste.

To realise these aims, seven further objectives were identified:

1. To analyse and discuss the extant literature germane to the development of technological innovation systems in the technological field of hydrogen production from waste.
2. To analyse and characterise, using Q methodology, the different expert communities involved in the sustainable production of hydrogen from waste in the UK and their involvement in the technological innovation system.
3. To develop a model to analyse the technological innovation system for hydrogen from waste using an interaction matrix approach, incorporating the results of the Q methodology.
4. To identify and characterise three regional case studies in the UK where hydrogen from waste activities are clustered.
5. To apply the model to these regional case study zones and make key observations and recommendations for each region.
6. To produce direct results for these case studies and discuss the possible implications of these results applying Q methodology and conceptual model together.
7. To identify the contribution to the field of technological innovation systems for the sustainable production of hydrogen from waste made by this doctoral research.

To meet the objectives described above: Following the literature review, a *Q methodology* survey was undertaken; this is a form of discourse analysis that allowed the researcher to gain insight into the perceptions of experts working in the fields contributing to the sustainable production of hydrogen from waste. The Q methodology used here was designed to extract different group identities from experts working in the same technological field. The results of the Q methodology led to the understanding of how these experts perceived their own role, and that of others, in the future innovation and production of hydrogen from waste technologies.

This method produced three group identities for the experts involved in the technological innovation system.

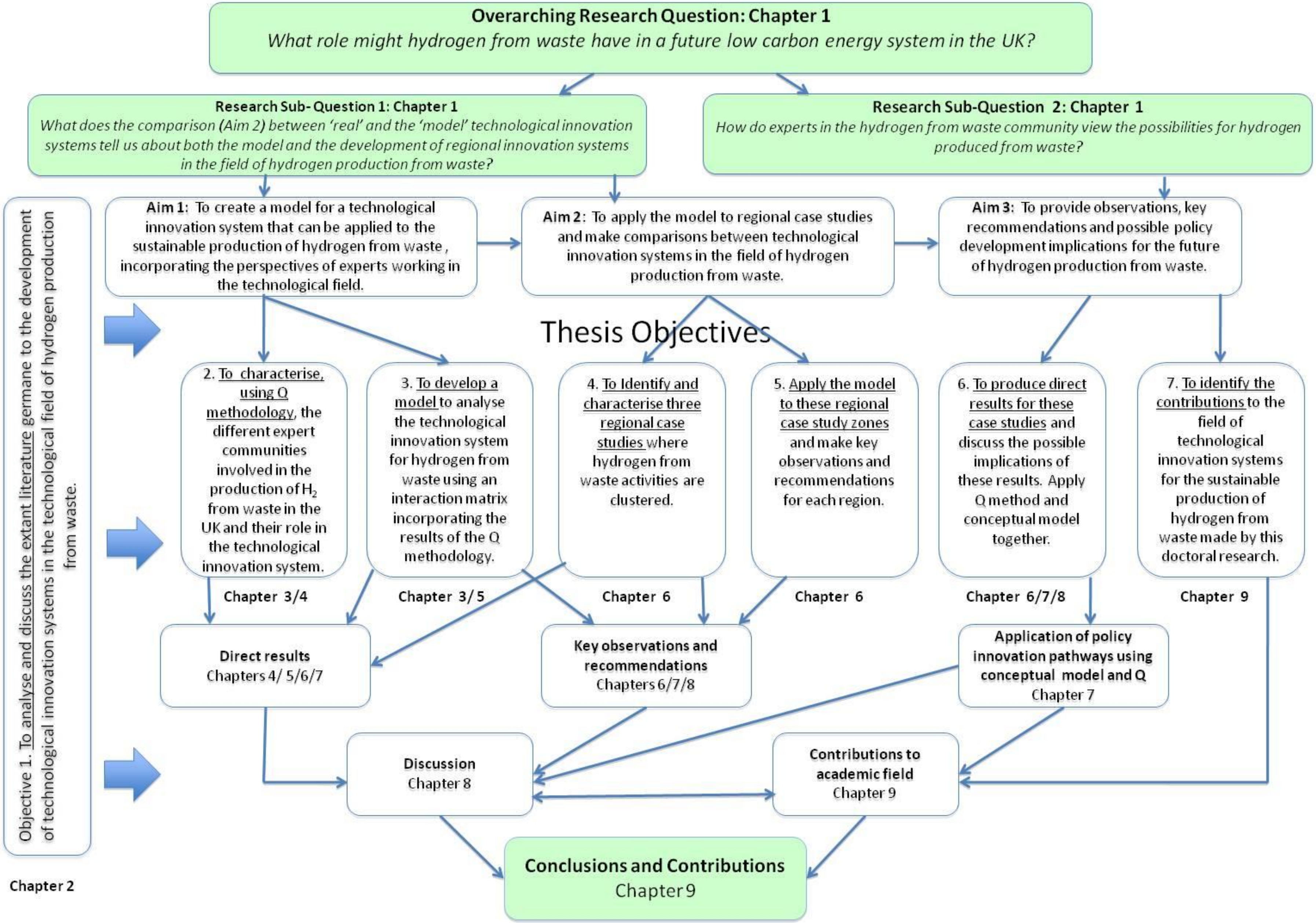
The identification of these distinctly different groups of experts fed into the development of the case study methodology investigating the technological innovation systems for the sustainable production of hydrogen from waste in Tees Valley, London and South Wales. Prior to the case study investigation, the new *Interaction Matrix–Technological Innovation Systems (IM–TIS)* model was developed, a seven by seven interactive matrix that identifies relationships between all the functions of innovation. The IM–TIS model was developed from the *Rock Engineering Systems* model and *the functions of innovation* model (1992; Bergek *et al.* 2008). An assessment of each region's technological innovation system against the original IM–TIS model was then undertaken. The case studies provide details of the current status of the technological innovation system in each case study region, as well as providing key observations in comparison to the original model and suggestions for the future to support the development of a low carbon society.

To show how these different methodologies could be combined to further inform the development, diffusion and commercialisation of technologies for the production of hydrogen from waste, the IM–TIS model was used to develop policy pathways. This is illustrated using a worked example of the process.

Further details on each of these methods are contained in the thesis structure in Section 1.5.

1.3 Doctoral Research Project Flow Diagram

The flow diagram in Figure 1.1 below provides a visual representation of the research questions, aims and objectives of this doctoral research. It shows where the different aims and objectives will be met and identifies the thesis chapters containing the relevant information and analysis.


Overarching Research Question: Chapter 1
What role might hydrogen from waste have in a future low carbon energy system in the UK?
Research Sub-Question 1: Chapter 1
What does the comparison (Aim 2) between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?
Research Sub-Question 2: Chapter 1
How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?
Objective 1. To analyse and discuss the extant literature germane to the development of technological innovation systems in the technological field of hydrogen production from waste.
Chapter 2
Aim 1: To create a model for a technological innovation system that can be applied to the sustainable production of hydrogen from waste, incorporating the perspectives of experts working in the technological field.
Aim 2: To apply the model to regional case studies and make comparisons between technological innovation systems in the field of hydrogen production from waste.
Aim 3: To provide observations, key recommendations and possible policy development implications for the future of hydrogen production from waste.
Thesis Objectives
2. To characterise, using Q methodology, the different expert communities involved in the production of H_2 from waste in the UK and their role in the technological innovation system.
Chapter 3/4
3. To develop a model to analyse the technological innovation system for hydrogen from waste using an interaction matrix incorporating the results of the Q methodology.
Chapter 3/5
4. To Identify and characterise three regional case studies where hydrogen from waste activities are clustered.
Chapter 6
5. Apply the model to these regional case study zones and make key observations and recommendations for each region.
Chapter 6
6. To produce direct results for these case studies and discuss the possible implications of these results. Apply Q method and conceptual model together.
Chapter 6/7/8
7. To identify the contributions to the field of technological innovation systems for the sustainable production of hydrogen from waste made by this doctoral research.
Chapter 9
Direct results
Chapters 4/ 5/6/7
Key observations and recommendations
Chapters 6/7/8
Application of policy innovation pathways using conceptual model and Q
Chapter 7
Discussion
Chapter 8
Contributions to academic field
Chapter 9
Conclusions and Contributions
Chapter 9

1.4 Thesis Structure

This section covers the layout of the thesis and provides details of each chapter.

1.4.1 Chapter 2 - Literature review

Chapter 2 presents, firstly, a description of the policy landscape for hydrogen production from waste. This provides a chronological view of the role of European and UK policies. A detailed review of the published literature relating to low carbon transitions, hydrogen technologies and futures follows. The review then makes connections between the transitions management theory and innovation systems. Finally, the review explores the history of the conceptual development of technological innovation systems and their relationship to the low carbon energy sector, along with the literature on functions of innovation models. Existing models developed to support technological innovation systems and examples relating to low carbon technologies are provided and reviewed.

Several academic literature strands have been drawn upon to inform the literature review for the specific needs of hydrogen production from waste. The review is socio-technical.

The academic literature covers material on hydrogen futures, hydrogen technologies, transition management and technological innovation systems, including functions of innovation. Germane publications were then selected from these fields to consider sustainable production of hydrogen from waste. The literature review recognises the importance of hydrogen storage and transportation as part of hydrogen futures and notes that the end-use for hydrogen may influence the production technique. However, these areas are of peripheral relevance to this research and are not critically reviewed in detail.

1.4.2 Chapter 3 - Methodology

Reasons for choosing the Q Methodology and Rock Engineering Systems (RES) approaches as methods are provided initially in this chapter. Attention then turns to how these methods were applied. This part is split into two main sections; the first describes the process of carrying out the Q methodology, including how and why particular study groups were chosen and how the results contributed to the second part of the methodology. This is supported by a critical review of the literature germane to low carbon technology investigation using Q methodology. The second main section describes the development of the case study investigation. The concepts behind the development of the IM–TIS conceptual model are covered. A review of RES literature covering its previous applications is given, including an in-depth review of the only previous innovation system application of the RES.

1.4.3 Chapter 4 - Q Methodology Results

The Chapter begins with a brief overview of the stepped approach to Q methodology. The three factor identities (*the hydrogen from waste advocate*; *the cautious environmentalist* and the *hydrogen technologists*) produced using the Q methodology are provided and accompanied by a short discussion.

1.4.4 Chapter 5 –Interaction Matrix – Technological Innovation System (IM–TIS) model

The IM–TIS model is a new model developed as part of this research to enable the investigation of technological innovation systems on a case by case basis. This chapter presents the process undertaken to develop this model. The adaptation of the RES model incorporating the functions of innovation model (Bergek *et al.* 2008) and the addition of the Indicators of Effectiveness, the Coefficient of Vulnerability and the overall effectiveness is described. The chapter then moves on to illustrate the application of the model to the UK regional case studies and London policy pathways.

1.4.5 Chapter 6 – IM–TIS Case Study Results (London, South Wales, Tees Valley)

The results of the application of the conceptual IM–TIS model to the three case study regions are presented. The case study regions and participants are described in detail. The results for each case study investigation are presented and comparisons to the ideal IM–TIS model made. A brief discussion of the results is given, including the rank and position of each of the functions of innovation, the indicators of and overall effectiveness of the system and the coefficient of vulnerability. Key observations for each region are made and some concluding comments on the process and study limitations given.

1.4.6 Chapter 7 – IM–TIS Model and Q Methodology: Illustrative worked example 'real situation' (London)

This chapter explores and demonstrates the importance of government policy in technological innovation systems for hydrogen from waste. An illustrative example of a further application of the IM–TIS model is provided in this chapter. Possible innovation system development pathways from the IM–TIS are worked through to demonstrate how this may apply to a 'real life' situation. A detailed description of the process is provided and some concluding comments given.

1.4.7 Chapter 8 – Discussion and Reflection

Discussion and reflections of the methods used and results obtained in this research is presented here. The success of the newly developed conceptual IM–TIS model in analysing technological innovation systems for hydrogen production from waste is examined. The role of policy and the functions of innovation are discussed. The overall success of the research project in addressing the research questions is also considered.

1.4.8 Chapter 9 – Conclusions and Contributions and Further Research

In this chapter, the thesis is concluded followed by suggestions for further research. Finally, the contribution of this research to the academic fields associated with technological innovation systems for the sustainable production of hydrogen from waste is given.

1.4.9 Appendices 1 and 2 CD Portfolio,—Supplementary data and figures, interviews

Appendix 1 provides further details of the raw qualitative data produced by the activities of the Q methodology survey and is included on the CD. The matrices used in the IM–TIS case studies and innovation system pathways are also included. Appendix 2 provides details of the interviews and surveys carried out throughout this research.

1.5 Concluding section

In this chapter, the research problem has been introduced and outlined. The three research questions have been covered and the policy landscape supporting this research outlined. In the following chapter, the extant literature relating to the research problem is critically reviewed. This includes low carbon and hydrogen futures, hydrogen from waste production technologies, innovation systems literature and conceptual models for the analyses of technological innovation systems.

1.6 References

Balat H. Kirtay E. Hydrogen from biomass: Present scenario and future prospects. International Journal of Hydrogen Energy 35 (2010) 7416–7426

Bergek A., Jacobsson S., Carlsson B., Lindmark S., Rickne A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (2008) 407–429

Breukers S., Hisschemöller M., Cuppen E., Suurs R. Analysing the past and exploring the future of sustainable biomass. Participatory stakeholder dialogue and technological innovation system research. Article in Press. Technological Forecasting and Social Change 2013

Carlsson B., Stankiewicz R. On the nature function and composition of technological systems. Evolutionary Economics (1991) 1 93–118

DECC (Department of Energy and Climate Change) 2011. UK Renewable Energy Roadmap. .

DECC 2012. DECC Science and Innovation Strategy 2012. UK Government.

European Parliament 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

Foxon T., Gross R., Chase A., Howes J., Arnall A., Anderson D. UK innovation systems for new and renewable energy technologies: drivers, barriers and system failures. Energy Policy 33 (2005) 2123–2137

Foxon T., Pearson P. Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime. Journal of Cleaner Production (2008) S148–S161

Freeman C. Technology, Policy and Economic Performance. Lessons from Japan. Pinter Publishers. 1987.

Hawkey D.J.C. District heating in the UK: A Technological Innovation Systems analysis. Environmental Innovation and Societal Transitions 5 (2012) 19–32

Hekkert M.P., Suurs R.A.A., Negro S.O., Kuhlmann S., Smits R.E.H.H. Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change 74 (2007) 413–432

Hudson J. A. and Harrison J. P. A new approach to studying complete rock engineering problems. *Q. J. Engng. Geol.*. Vol. 25, No. 2, 1992, 93-105. .

IPCC 2007. Intergovernmental Panel on Climate Change Fourth Assessment Report. IPPC

IPPC 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation. IPPC.

Johnson A. Functions in innovation system approaches, mimeo. Department of Industrial Dynamics, Chalmers University of Technology, Sweden. 1998.

Markard J., Raven R., Truffer B. Sustainability Transitions: An emerging field of research and its prospects. Research Policy 41 (2012) 955–967

McDowall W. Technology roadmaps for transition management: The case of hydrogen energy. Technological Forecasting and Social Change 79 (2012) 530–542

McDowall W., Eames M. Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature. Energy Policy 34 (2006) 1236–1250

Negro S.O., Hekkert M.P., Smits R.E. Explaining the failure if in the Dutch innovation system for biomass digestion—A functional analysis. Energy Policy 35 (2007) 925–938

Negro S.O., Suurs R.A.A., Hekkert M.P. The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system. Technological Forecasting and Social Change 75 (2008) 57–77

Shuckburgh E., Robison R., Pidgeon N. Climate Science, the Public and the News Media. Summary Findings of a survey and focus groups conducted in the UK in March 2011. September 28th 2012

Stern N. The Economics of Climate Change. Executive Summary. The Stern Review 2006.

Suurs R.A.A., Hekkert mM.P., Kieboom S., Smits R.E.H.M. Understanding the formative stage of technological innovation system development: The case of natural gas as an automotive fuel. Energy Policy 38 (2010) 419–431

Truffer B., Markard J., Binz C., Jacobsson S. (2012). Energy Innovation Systems. Structure of an emerging scholarly field and its future research ditrections. A literature review. Chalmers University, Gothenburg. EIS November.

UK Parliament 2008. Climate Change Act 2008.

2 UK Policy Landscape and Literature Review

This thesis presents research that investigates the roles of actors, institutions and networks involved in innovation in the hydrogen production from waste field. Drawing on several strands of literature, the research has been conducted using a mixed methods approach and is socio-technical in nature. Based on this, the literature review is presented in a manner that brings together these different strands of literature and provides background to and current thinking in the field of technological innovation systems that relate to hydrogen production from waste.

This chapter fulfills the requirements of Objective 2: *To analyse and discuss the extant literature germane to the development of technological innovation systems in the technological field of hydrogen production from waste. In order to set the context, the chapter begins by reviewing the policy landscape in section 2.1.* In section 2.2, Energy transitions and transition management theory are then reviewed showing the relationship between these approaches and the innovation systems theory in section 2.3. The review then moves, in Section 2.4, to consider hydrogen technologies and their future from the technical perspective. This is followed, in sections 2.5 and 2.6, by a critical review of the major conceptual, technological and methodological developments in the field of technological innovation systems that relate to hydrogen production from waste. Gaps in current thinking and opportunities for research are provided in section 2.7. In section 2.8, a discussion of possible methods to address the research gaps is given and section 2.9 concludes the chapter.

In this chapter, the literature germane to the research problem is critically reviewed. The literature comes from four different but related academic strands of literature. They include:

- Transition management;
- Hydrogen Futures;
- Hydrogen from waste technologies; and
- Innovation systems and functions of innovation.

2.1 UK and European policy landscape influencing hydrogen production from waste

It is recognised (Truffer *et al.* 2012) in the literature considering energy and low carbon related innovation that growing attention to hydrogen production from waste is partly due to the development of energy policies in many countries. Moreover, in the UK national energy and waste policies are often developed following changes to European legislation. As described in section 1.1.1, in the UK there are many policies and roadmaps that could influence the innovation and advancement of technologies that support the production of hydrogen from waste. Therefore, in order to ensure that the review of government documents and other literature remains germane, documents were selected based on at least two of the following criteria:

1. Discuss the role of hydrogen from waste or the role of energy from waste.
2. Indicate that by-products from waste processes should be used to create energy or heat.
3. Be supportive of the concepts of sustainable development.
4. Indicate a need for greater innovation in renewable energy technologies.

Based on these criteria, a number of policies, strategies and roadmaps from the EU and national tiers of government were selected and are described. The selected European and UK policy and strategy documents are not intended to be a comprehensive list of the government documents that may influence the sustainable production of hydrogen from waste. Documents were prioritised with the aim that the policies and strategies described in this section provide a clear picture of the range of policies that may form part of the technological innovation system. Policy and strategy documents were used to provide an impression of how the policy landscape can be interpreted for the promotion of hydrogen production from waste.

In this section, four key EU legislative directives and policies are described chronologically. These are then brought together at the end of the section. Included are three Directives of the European Parliament: the Landfill Directive 1999/31/EC (European Parliament 1999), the Waste Framework Directive 2008/98/EC (European

Parliament 2008), and the policy on low carbon technologies and Directive 2009/28/EC (European Parliament 2009) on the promotion of the use of energy from renewable sources. In addition to these directives, the Roadmap for Moving to a Low Carbon Economy in 2050 (European Parliament 2011) is also described. The description of these government documents aims to outline the European policy landscape supporting the development of hydrogen production from waste. The policies and strategies produced at EU, UK national and regional levels may influence the development of new technologies and the regional activities of local authorities, universities and businesses towards hydrogen production from waste. However, this is not always the case, since government policy and strategy are not the only catalysts for research in academia and business.

Waste related European directives have a long history of policy influence in the UK. The first Waste Framework Directive, Directive 75/442/EC (European Parliament 1975), was released in 1975. The Directive made the requirement: *to develop waste management plans in each nation*. It provided the impetus for the development of waste management strategies across member states including the UK. It also provided the first European definition of waste and:

- Encouraged proper disposal using a designated authority;
- Promoted reuse and recovery of materials;
- Identified the environmental risks associated with mismanagement of waste; and
- Required the development of waste management plans in each nation and the collection of waste data

Nevertheless, this Directive was considered to lack a consistent application across Europe due to poor definitions in the Directive and a lack of minimum standards for issuing permits (Marcousé 2008). The Directive was overhauled in 1991, leading to a better definition of waste, and definitions for disposal and recovery, as well as requirements for wastes collection and disposal (European Parliament 1991). The Waste Framework Directive was again revised in 2008, creating Directive 2008/98/EC (European Parliament 2008) that provides further guidance for decision makers on what is or is not waste.

In the UK, numerous waste strategies have been produced over the last fourteen years. These include: Waste Strategy 2000 (DEFRA 2000), relating to England and Wales, Wise about Waste 2001 (Wales only) (Welsh Government 2001), Waste Strategy for England 2007 (DEFRA 2007), Towards Zero Waste 2010 (Wales only) (Welsh Government 2011), Waste Policy Review for England 2011 (DEFRA 2011) and London's Wasted Resource 2011 (London Assembly 2011). Further strategies have been developed for other UK regions, i.e. Scotland (Scottish Government 2010), Northern Ireland (DOENI 2006), the Isle of Man (Isle of Man 2012) and the Channel Islands (Jersey Government 2005).

Other European Directives have played a significant role in influencing national agendas, including those of the UK. For example, section 5 of the Landfill Directive 1999/31/EC (European Parliament 1999) suggests that bio-waste contributes to 3% of EU greenhouse gas emissions and the Directive requires member states to reduce their emissions to 35% of 1995 levels by 2016 (2020 in some states). The directive does not provide any direction on how this bio-waste should be managed, only that the most significant benefits from this waste type would be through composting and the production of biogas (European Parliament 1999).

To appreciate further how the Directive (European Parliament 1999) has influenced UK policy and strategies, actions relating to this Directive can be found in the Government Review of Waste Policy in England 2011 (DEFRA 2011) and the UK Anaerobic Digestion Strategy and Action Plan 2011 (DEFRA 2011). In (DEFRA 2011), the UK government reaffirms its commitment to support efficient energy recovery from waste that delivers environmental benefits, reduces carbon impacts and produces economic gains. They describe this policy as *getting the most out of waste and not getting the most waste into energy recovery* (DEFRA 2011 pg: 62). This review document (DEFRA 2011) suggests that anaerobic digestion offers a positive solution to food waste. It provides a further commitment to work with industry to deliver the Anaerobic Digestion Strategy and Action Plan (DEFRA 2011).

The Anaerobic Digestion Strategy and Action Plan (DEFRA 2011) also published in 2011 does not, however, directly indicate that hydrogen may be produced from waste through anaerobic digestion. The strategy does promote the use of the biogas produced from the digestion process (mostly methane and carbon dioxide) to fuel vehicles and inject into the gas grid (DEFRA 2011 p. 14). The conversion of biogas to produce hydrogen is one area considered by this research.

The absence of explicit direction for hydrogen from waste in these policy and strategy documents may be a result of the emerging nature of hydrogen from waste technologies, which is explained further in section 2.3.

Considering the influence of European Directives on UK energy/waste policy and strategy development, a more recent directive is the Directive 2009/28/EC (European Parliament 2009) on the promotion of the use of energy from renewable sources. This directive sets targets for EU member states to reach a 20% share of final energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector. The Directive also makes a requirement on member states to produce action plans establishing pathways for renewable technologies including biofuels. It is notable that this Directive also established sustainability criteria for biofuels limiting the conversion of land for bio-fuel growth (European Parliament 2009).

This direction from the European Parliament has filtered down into the UK in two ways. Firstly, the UK Government has a policy under the Climate Change Act 2008 (UK Parliament 2008) to reduce the UK's greenhouse gas emissions (GHG) by 80% by 2050. (The Climate Change Act was described in section 1.1.1.) In order to achieve this, they have made a commitment to invest in low carbon technologies that reduce greenhouse gas emissions and transform the power sector (UK Government 2013). The UK Government could be considered as leaders in reducing GHG emissions as it (UK Parliament 2008) set this target into law prior to (European Parliament 2009) pre-empting the European directive.

Secondly, the UK government has produced an Action Plan for Renewable Energy Sources (UK Government 2010) as required by Article 4 of the Directive 2009/28/EC (European Parliament 2009). A UK renewable energy roadmap (DECC 2011) to support delivery of their policy to reduce GHG emissions by 80% by 2050 was also produced. These are the government documents considered most relevant here in the context of the production of hydrogen from waste. The UK Government has also produced a number of other strategies and action plans that address other parts of the low carbon agenda: for example, home insulation, carbon capture and storage, transport, GHG emissions from agriculture and carbon budgets (UK Government 2013).

As noted in Chapter 1, the National Renewable Energy Action Plan (UK Government 2010) lays out the task ahead for the UK to meet the requirements of Directive 2009/28/EC (European Parliament 2009) to achieve 15% of its energy consumption from renewables by 2020 (European Parliament 2009). This is in comparison to the 1.5% achieved in the UK in 2005 (UK Government 2010 p. 2). The outlook for hydrogen produced from renewables reflected in this action plan was bleak and it did not seem to have been considered as a renewable source of energy offering any significant potential reductions in GHG emissions by 2020. Table 12 in the action plan shows the estimated total contribution expected from each renewable energy technology in the UK to meet the binding 2020 targets and the indicative interim trajectory for the shares of energy from renewable resources in the transport sector 2010-2020. The contribution for hydrogen produced from renewables is zero across all years to 2020 (UK Government 2010 p. 156).

The 2011 UK Renewable Energy Roadmap (DECC 2011), although not explicitly referring to hydrogen from waste or bio-hydrogen, is more positive in its outlook for hydrogen in general. Support for hydrogen fuel cell cars in the interim period of 2014 to 2020 is given, along with a commitment of £400m to support the purchase of plug-in and hydrogen fuel cell cars through the Plug-in Car Grant (DECC 2011 p. 102). The Carbon Plan (UK Government 2011) does not identify any position for hydrogen in the future. The UK Renewable Energy Roadmap (DECC 2011) positions hydrogen in the transport sector only for the near future. These documents do not help yield a clear picture for establishing how the UK Government currently views hydrogen production from any renewable energy source.

While the European Parliament is responsible for the production of EU Directives, the European Commission also produces strategic directions. In 2011 in a communication to the European Parliament, the European Commission (European Commission 2011) illustrated their vision for Europe moving forward to a low carbon economy by 2050. In this strategic document, there are three key points that could indicate further developments for hydrogen from waste. They are as follows.

1. Technological innovation can help the transition to a more efficient and sustainable European transport system by acting on three main factors: vehicle efficiency through new engines, materials and design; cleaner energy use through new fuels and propulsion systems; and better use of networks and safer and more secure operation through information and communication systems.

2. The synergies with other sustainability objectives (such as the reduction of oil dependence, the competitiveness of Europe's automotive industry as well as health benefits, especially improved air quality in cities) make a compelling case for the EU to step up its efforts to accelerate the development and early deployment of electrification, and in general, of alternative fuels and propulsion methods for the whole transport system.

3. Sustainable biofuels could be used as an alternative fuel especially in aviation and heavy-duty trucks, with strong growth in these sectors after 2030. In case electrification were not to be deployed on a large-scale, biofuels and other alternative fuels would need to play a greater role to achieve the same level of emissions reduction in the transport sector. (European Commission 2011).

This section has illustrated how the European Parliament and Commission have agency over the UK through the production of Directives and strategic documents. This is evident in the policy landscape presented here for the UK. However, as previously suggested, the European Parliament and Commission are not the only influences on UK Government policy development. Other key influences on policy development come from the academic and business sectors in the UK; these will be discussed in more detail in section 2.2. Foxon & Pearson (2008) recognise the "need to translate academic insights" for use by policy makers. Evidence produced from research innovation and testing may influence policies for renewable technologies. Developments in taxation and incentives that support renewable technologies may be influenced directly by the business sector. Foxon *et al.* (2005) identify the need for a stable and consistent policy framework for renewable technologies in the UK as a common theme emerging from the analysis of innovation systems surrounding renewable energy technologies in the UK.

These policies and strategies from Europe and the UK provide an insight into the government's vision of the role that hydrogen from waste and energy from waste might play in a future low carbon energy system in the UK. From the policies and strategies presented here, it could be argued that hydrogen production from waste is not considered in its own right, but may contribute to a reduction in GHG emissions and meeting targets for both waste and energy in the UK. The strategies presented in this policy landscape show that the UK government neither advocates nor opposes technologies that support hydrogen from waste. The insight gained from these policies has provided guidance in the development of the aims and objectives for this research project, as well as beginning to address the overarching research question: *"What role might hydrogen from waste play in a future low carbon energy system in the UK?"*

In order to understand this research question further, the concept of technological innovation systems and functions of innovation have been utilised. Technological innovation systems are reviewed in detail in Section 2.4 and again with specific reference to this research in Chapter 3 (Methodology) Section 3.6. The concept of technological innovation systems (Carlsson & Stankiewicz 1991) is to develop, diffuse and commercialise technologies by bringing together academia, business and government in a particular sector to bring technologies into use. In this research, the technological field is the sustainable production of hydrogen from waste. Taking the concept of technological innovation systems and breaking it down further into the different functions of innovation (Bergek *et al.* 2008), the role of government, private business and academia and the relationship between them is considered. As described in Section 2.4, government policy plays an important role in the development and success of the technological innovation system. The reverse may also be true, in that emerging technology presenting solutions to problems like green house gas emissions or poor localised air quality may influence the development of government policies. The technological innovation system can map out these interactions and relationships. It is therefore important that the policy landscapes relating to a given technological field are understood as this may allow for influencing the system to produce diffusion and commercialisation of the technology in question.

2.2 Critical review of literature

The analysis of the literature presented in this Chapter aims to help identify whether and how hydrogen produced from waste has potential value in a future low carbon energy system. It may also be possible to show how the hydrogen could be produced, which technologies are showing the greatest potential, and why. This critical review aims to show how important elements of research into technological innovation systems for hydrogen production from waste have developed to date and presents a critical analysis of the different strands of literature that feed into this research. The rest of this chapter is structured as follows. It begins in section 2.2.1 by looking at the concept of hydrogen futures historically and whether the reasons for and against this concept have changed over time. The review then moves on in section 2.3 to describe the role innovation systems play in low carbon transitions and the relationship between this literature and the literature on transitions management and innovation systems. The technologies involved in the production of hydrogen from waste are then considered in section 2.4. This is followed by an analysis of the innovation systems literature, illuminating the strengths and limitations of different approaches to understanding and developing innovation systems in section 2.5.

Attention is turned in the later sections of the review to the functions of innovation and whether a mixed methods approach applied from a different perspective, i.e. from the experts involved in the technological field, can assist in the deployment of hydrogen from waste technologies. This concept is investigated further in Chapter 3 where literature reviews for the methods used are provided. The final section of the review in section 2.6 addresses the literature surrounding innovation systems and the *functions of innovation*. This is complemented by a critique of the conceptual models for the analysis of technological innovation systems. Justification for the choice of conceptual model used in the experimental phase of this research will be covered in Chapter 3 (Methodology) section 3.2. From this point, when all the evidence has been presented, the gaps in the research are identified.

2.2.1 Hydrogen and the transition to a low carbon future

To establish an environment where hydrogen from waste can be progressed as an energy vector, it is important to understand its potential position within the larger picture of a low carbon transition. The transition includes many changes in technologies for energy production, as well as in energy conservation and addressing energy using behaviours. The academic papers reviewed in sections 2.2, 2.3 and 2.4 are taken from many different countries, both European and non-European. The publications reviewed were chosen differently for each section of the literature review. This was due to the complexity of drawing together germane literature from each strand to ensure that the research problem was accurately represented. The method used for choosing publications is given in each section of this review.

From the publications critiqued here in the field of low carbon transitions and hydrogen futures, it is suggested that hydrogen technologies offer a potential solution for shared concerns in these different countries. The UN Climate Change Conference in Doha 2012 agreed to a new commitment period (United Nations 2012) for GHG emissions and affirmed a previous decision to adopt a new global climate pact by 2015. This commitment suggests that governments around the world are beginning to share common values about climate change and reducing green house gas emissions (GHG). This common ground may be created as a result of global political pressure, localised air quality and smog issues or other specific concerns within each nation. In many countries, government policies influence the research carried out in each nation in order to meet a particular strategic objective. The directives, policies, strategies and roadmaps developed by the UK government and described in section 2.1 provide some direction for the development of academic research. It cannot be said that this is always the case: governments may invest to solve a particular issue, but blue sky research will continue. The literature reviewed in section 2.1 is a combination of government influenced research and blue sky research.

2.2.1.1 'Our low carbon future': transitions to low carbon in the UK

This section focuses on the role of hydrogen within the transition to a low carbon future in which GHG emissions are reduced through use of new low carbon technologies and a reduction in the use of fossil fuels. There is a large academic literature debating energy transitions. This section will focus on describing aspects of UK Government transitions policy that concern low carbon futures and could be considered to support hydrogen as an energy vector.

As noted, the Climate Act 2008, introduced with all-party support, committed the UK to stringent emission targets. The Low Carbon Transition Plan (HM Government 2009) and the Carbon Plan (HM Government 2011) were subsequently put in place by Labour and Conservative/ Liberal Democrat Coalition governments, respectively, to provide a set of measures and incentives to achieve these targets.

In 2009, a report by Chatham House (Chatham House 2009) presented a number of findings that the government will have to address to ensure that their overall vision in their Carbon Plan is realised. The primary findings from Chatham House relate to hydrogen concern energy storage through battery fuel cells and the report offers an interesting view on hydrogen technologies and their end uses. The end-uses of hydrogen may have an influence on the method of producing it and, because of the limited government resources discussing hydrogen production, this report is considered particularly relevant here.

Four findings from Chatham House (2009) are given below:

1. *Policy-makers managing the transition to a global low carbon economy will struggle when making the critical choices unless they have a clear understanding of the range of technological options available from different sectors within specific time horizons, and they will also require an appreciation of how their technological interactions will affect industrial structures. Technological innovation and diffusion take too long under business-as-usual practices.*

2. *Analysis shows that inventions in the energy sector have generally taken two to three decades to reach the mass market. This time lag is mirrored by the time it takes for any patented technology to become widely used in subsequent inventions. Data on the top 30 most-cited patents from each of the six sectors examined here indicate that it takes between 19 and 30 years with an average of around 24 years. The process of registering a patent can take up to three years. The diffusion time for clean technologies globally will need to be halved by 2025 to have a realistic chance of meeting climate goals.*

3. *Targeted policies will be needed if accelerated and wholesale deployment of these technologies is to be achieved.*

4. *Companies and institutions in OECD countries will determine the speed of diffusion of the most advanced energy technologies in the next decade. Innovation and technological development primarily take place within the OECD countries and companies (Chatham House 2009, p. vii).*

These findings are reflected to some degree in the UK Government's Carbon Plan (UK Government 2011) in terms of seeking out the technologies and creating competitiveness. They provide a clear message that the systems supporting technological development may not be adequate at the present time. The suggestions from (Chatham House 2009) are specific, such as, halving the diffusion time from twenty four to twelve years for new technologies. The (UK Government 2011) Carbon Plan uses less powerful wording: for example, *"the UK will prepare for the future by demonstrating and deploying the key technologies required for the 2020s".* Another example is: "*By developing options now, the UK will not only reduce the costs of* *deploying these technologies in the 2020s. It will also gain a long-term competitive advantage in sectors that play to our comparative strengths*."

According to Chatham House (2009), however, the average time for deployment is twenty-four years, delaying any options created today to 2035, well beyond their target dates. The language used in the Carbon Plan (UK Government 2011) shown in the following paragraphs does not show a clear commitment to reducing deployment times. Words such as 'prepare' and 'develop' may not give the impression that sufficient action will be taken. These findings suggest that investigating the technological innovation system for hydrogen and wider renewable technologies will be useful. This includes viewing the problems faced in the innovation systems from a different perspective i.e. that of hydrogen and energy production rather than end use. Technological innovation systems will be reviewed in section 2.4.

The Carbon Plan (2011) is a strategic document produced by the UK Government to address sections 12 and 14 of the Climate Change Act 2008 (HM Government 2008). Section 12 sets out the *duty to provide indicative annual ranges for the net UK carbon account*. The 2008 Act also introduced carbon budgets, to be recommended by the independent Climate Change Committee, to help ensure that the UK will meet its target of reducing UK emissions by at least 80% by 2050; section 14 sets out *the duty to report on proposals and policies for meeting UK carbon budgets*. The Carbon Plan document presents a vision for a low carbon UK by 2050 and indicates how this should be achieved over the next two decades.

The key points are given below (UK Government 2011) and have been extracted from their strategic vision:

1. *In the next decade the UK will complete the installation of proven and cost effective technologies that are worth installing under all future scenarios. The fuel efficiency of internal combustion engine cars will improve dramatically, with* CO_2 *emissions from new cars set to fall by around a third. Many of our existing coal-fired power stations will close, replaced primarily by gas and renewables. More efficient buildings and cars will cut fuel costs. More diverse sources of electricity will improve*

energy security and reduce exposure to fossil fuel imports and price spikes.

2. *Over the next decade the UK will also prepare for the future by demonstrating and deploying the key technologies needed to decarbonise power, buildings and road transport in the 2020s and beyond. Rather than picking a single winner, this plan sets out how the UK will develop a portfolio of technologies for each sector....*

3. *In transport, ultra-low emission vehicles including fully electric, plug-in hybrid, and fuel cell powered cars are being developed. In buildings, the technologies will include air- or ground-source heat pumps, and using heat from power stations. Both of these are solutions proven by their use in other countries.*

4. *During the 2020s each of these technologies – low carbon electricity, low carbon cars and low carbon heating – will move towards mass roll-out. We estimate that between 40 and 70 gigawatts (GW) of new low carbon power will need to be deployed by the end of the decade. Emissions for the average new car will need to fall to between 50 and 70 gCO_2/km, compared with 144 gCO_2/km in 2010. Between 21% and 45% of heat supply to our buildings will need to be low carbon by 2030.*

5. *By developing options now, the UK will not only reduce the costs of deploying these technologies in the 2020s. It will also gain a long-term competitive advantage in sectors that play to our comparative strengths...*

6. *To 2030 and beyond, emissions from the hard-to-treat sectors – industry, aviation, shipping and agriculture – will need to be tackled. This will require a range of solutions to be tested by at the latest, the 2020s, including: greater energy efficiency; switching from oil and gas to bioenergy or low carbon electricity; and carbon capture and storage for industrial processes (UK Government 2011, p. 4–5).*

Throughout this strategic document, hydrogen is considered as a fuel for fuel cell batteries and primarily for use in vehicles (UK Government 2011). The direction and vision provided in this strategy supports the further exploration of new and emerging hydrogen production techniques and understanding of their possible roles within the energy system. Thus, the UK Government's 2011 Carbon Plan presents a positive view of how the transition to a low carbon future may happen. Prior to the report and supporting this positive view, some authors have presented hydrogen infrastructure and associated technologies as offering significant cuts in CO_2 emissions (Strachan *et al.* 2009).

Having summarised the UK Government's overall policies for energy transitions, a critical review of the academic literature on hydrogen futures, energy transitions and transition management may provide insight into how these transitions could be accomplished.

2.3 Hydrogen futures

In this section, the different dimensions of hydrogen futures are considered. Firstly the idea of hydrogen as a renewable energy source is introduced, along with the different options for hydrogen production. The section then moves on to discuss the roots of the hydrogen economy concept and the advantages and limitations presented in the associated academic literature.

Hydrogen (H_2) is not in itself an energy source: rather it is a carrier of energy, i.e. an energy vector, and is found in compounds such as water (H_2O), various hydrocarbons including oil, gas and coal and in hydrocarbon gases like methane (CH_4). H_2 does not occur directly and energy is required to liberate the H_2 from these compounds (Blanchette 2008). H_2 offers the ability to be stored; it can then be transported and used in fuel cell batteries for stationary or vehicle applications (Hetland & Mulder 2007). These different uses for H_2 fuel are indicated in the literature relating to hydrogen futures. This literature provides some indication of the potential role of hydrogen produced from waste in a transition to a low carbon UK energy system, where renewable energy resources are of growing interest, including wind, solar, hydro power and nuclear.

2.3.1.1 Hydrogen production techniques

Hydrogen can be produced using a number of different process techniques, some of which are appropriate for producing hydrogen from waste. These are briefly described below in order to provide the background for the following section on hydrogen futures literature. The descriptions below draw on (EERE 2010):

Natural gas reforming (EERE 2010): this is where the hydrogen is liberated from hydrocarbon gases using high temperature steam, called *steam methane reforming*. Alternatively partial oxidation, where hydrogen is produced by burning methane with air, can be used to produce a *synthesis gas* or *syngas*, which is reacted with steam to produce further hydrogen.

Gasification (EERE 2010): this is the process by which coal or *biomass* is converted into gas by applying heat under pressure in the presence of air, oxygen and steam. A syngas is then produced and reacted with steam to produce a gas stream with increased hydrogen content that is subsequently separated from the carbon in the gas stream. It is suggested that this technique could also be combined with carbon capture and storage to reduce carbon emissions.

Renewable liquid reforming (EERE 2010): this uses biomass to create *bio-fuels*, such as ethanol or bio-oil. These fuels can then be reacted with steam to produce hydrogen. The bio-fuel is easily transported allowing the hydrogen production to take place at the end-use destination.

Low carbon electrolysis (EERE 2010): this is a process that uses an electrical current to split water into hydrogen and oxygen. The electricity used to generate the current can be obtained from many sources, but to reduce GHG emissions wind, solar, geothermal and wave, as well as other renewable generated electricity, can be used. Electrical currents can also be generated by nuclear power and coal and natural gas with carbon sequestration.

High temperature thermochemical water splitting (EERE 2010): this is another water splitting technique that uses high temperatures produced by solar concentrators or nuclear reactors to drive a series of chemical reactions to split water into hydrogen and oxygen.

Biological (EERE 2010): these are processes that use microbes such as green algae and *cyanobacteria* to produce hydrogen by splitting water in the presence of sunlight. This is a by-product of their natural metabolic cycle. There are some microbes that can produce hydrogen directly from biomass. *Anaerobic digestion* and other fermentation processes, such as, *dark fermentation* are considered as biological processes.

Photoelectrochemical (EERE 2010): this is a process where hydrogen can be produced directly from water using sunlight and specially designed semiconductor materials. The semiconductors use the energy from the sunlight to split the water into hydrogen and oxygen (EERE 2010).

From the above summaries of hydrogen production techniques, it can be seen that there are many possibilities for producing hydrogen using different feedstocks. However, despite the promise of hydrogen to reduce GHG emissions and secure energy supplies, many of these hydrogen technologies are not fully mature. It is notable that 90–95% of hydrogen produced globally today is through steam methane reforming of natural gas; this is the most mature technology mentioned above (EERE 2010; Hetland & Mulder 2007).

2.3.2 Hydrogen future concepts

General Motors have been described (Andrews & Shabani 2012) as first envisioning the concept of the hydrogen society that later developed into that of the hydrogen economy. The hydrogen society is a world where hydrogen is the normal source of energy and fuel, whereas the hydrogen economy is described as a proposed system of delivering energy using hydrogen. This was in the 1970s, at a time when primary concerns were for the loss of accessibility to low priced oil and gas following exponential growth in their use and the oil price shocks of 1973–74 and 1979–80. The oil crisis of the 1970s spurred governments, businesses and academics to look at alternatives to the fossil fuel energy paradigm (Andrews & Shabani 2012), where the burning of fossil fuels is central to the production of fuel and power.

Initially, when the idea of the hydrogen economy was first investigated, it was at a time when securing energy supplies and the economics of fossil fuels were the priorities, whereas climate change concerns were only dimly recognised, if at all (Andrews & Shabani 2012). The initial explorations into alternative fuels were short lived due to the changing market conditions of the 1980s, particularly falling oil prices from 1985–86 (Blanchette 2008). The evidence presented in the policy landscape in section 2.1 provides an acknowledgement of the impact that further developments in scientific evidence relating to the causation of climate change since the 1990s has had on EU and UK government policy. This has also influenced research into the hydrogen economy in non-EU countries, including the USA, Canada, Norway and Australia (Hajimiragha *et al.* 2011; Andrews & Shabani 2012; Hetland & Mulder 2007; Blanchette 2008).

Hydrogen is often seen as offering a fuel with two advantages over fossil fuels: having relatively negligible environmental emissions; and addressing issues of potential scarcity as the most abundant element in the universe (Brey *et al.* 2006; Blanchette 2008). However, the barriers to the realisation of a hydrogen future include: infrastructure limitations, economic viability concerns and the lack of clear leadership towards this future (Blanchette 2008). Criticisms of academic, government and corporate studies aimed at the potential for a hydrogen economy or future have often concerned their over-reliance on unproven and uncommercialised technologies (Hajimiragha *et al.* 2011) to achieve this future. These criticisms are likely to have raised potential public and private investors' concerns about technological and financial risk and are reducing take up of these technologies. Consequently, the technologies associated with hydrogen production may be considered to present too great a risk, both socially and economically, to be a valuable element in a low carbon transition.

The hydrogen economy, also often referred to as a hydrogen future, has been explored and presented through academic literature, government and business strategies and roadmaps. These present different visions and scenarios of what a hydrogen economy may look like (McDowall & Eames 2006). The UKSHEC Hydrogen Vision working paper

No. 9 (Eames and McDowall 2005) presents six possibilities for long-term visions of a UK hydrogen economy (see Figure 2.1). These possible futures are envisioned around 2040, a timeframe considered far enough into the future to render technological and infrastructural barriers proposed in 2005 obsolete. The possible hydrogen futures explained in Figure 2.1 are split into transport futures and transport and energy services futures. Four transport futures are presented compared to two energy services futures.

It is notable that, at the time this paper was produced, the focus was towards the end use of hydrogen for transportation uses and not for energy services more generally (Eames & McDowall 2005). In more recent publications (Hultman & Yaras 2012 and Andrews & Shabani 2012), the focus is less on visualising how hydrogen will be used and what that future may look like; instead, there is emphasis on how hydrogen may contribute to reducing GHG emissions, create economic growth through new technology development and implementation, and provide greater energy security for individual nations.

	Summary of UK hydrogen futures	
Transport Futures	Central Pipeline	Hydrogen has become the dominant transport fuel, and is produced centrally from a mixture of clean coal and fossil fuels (with carbon capture and sequestration), nuclear power, and large-scale renewables. Hydrogen is distributed as a gas by dedicated pipeline.
	Forecourt reforming	Hydrogen produced locally by natural gas is the dominant transport fuel. The existing natural gas network provides the delivery infrastructure, and hydrogen is generated on-site by steam methane reforming at the refuelling station.
	Liquid Hydrogen	Liquid hydrogen produced by nuclear power and large-scale renewable installations has become the dominant transport fuel. There is an international market in liquid hydrogen. This is largely a scenario of substitution, with current energy and transport paradigms remaining unchanged.
	Synthetic liquid fuels	Renewably produced hydrogen again provides the dominant transport fuel. In this case, however, it is 'packaged' in the form of synthetic hydrocarbon, such as methanol, to overcome the difficulties of hydrogen storage and distribution. The carbon for fuel synthesis comes from biomass and from the flue gases of carbon intensive industries.
Transport and Energy Services Futures	Ubiquitous Hydrogen	Renewably produced hydrogen is a major energy carrier for heat and power as well as the dominant transport fuel. A hydrogen pipeline grid serves most buildings. Many homes and businesses use fuel cell CHP systems running on hydrogen, and it is common to refuel your vehicle at home. Hydrogen is produced from a mix of larger centralised and smaller-scale distributed renewables and biomass.
	Electricity Store	Hydrogen, produced through onsite electrolysis, is the dominant road transport fuel, and also plays a vital role in overcoming the intermittency problems of renewables-based electricity system. Hydrogen production is flexible, and can respond to variable electricity supply conditions, easing load-balancing. Since hydrogen is produced onsite, it requires no distribution infrastructure. Locally-stored hydrogen provides back-up power for domestic and commercial CHP units at peak times of electricity demand/limited supply.

Table 2.1 Box 1. Summary of UK Hydrogen Futures (excerpt from Eames & McDowall 2005 p. 1)

Considering these visions, it can be suggested that hydrogen produced from fossil fuels and large low carbon installations including nuclear are considered most likely. Only the vision called 'Ubiquitous Hydrogen' mentions the use of biomass as a possible feedstock option. This vision promotes the distributed small-scale production of hydrogen, as well as centralised large scale production.

Waste as a feedstock for hydrogen production is often considered in tandem with biomass. As previously stated (Hetland & Mulder 2007), between 90–95% of hydrogen globally is produced from natural gas reforming. However, few hydrogen economy and futures publications have given substantial consideration to waste and biomass as a feedstock. Balat (2008) includes the possibilities for biomass as a feedstock and identifies specifically organic waste and wastewater as offering an economical and environmentally friendly way to produce hydrogen.

Crucially, the need for a hydrogen infrastructure is universally recognised. McDowall & Eames (2006), drawing on their 2005 paper and the literature, present two types of infrastructure—described as decentralised and centralised architectures. The decentralised architecture is based on the local production of hydrogen from electrolysis, biomass and steam methane reforming of natural gas. It is suggested that the decentralised architecture addresses the infrastructural barriers facing the transition to a hydrogen economy. In some instances, this decentralisation of hydrogen production and distribution may be seen as an interim position as the new more centralised and national hydrogen infrastructure is built up (McDowall & Eames 2006). The centralised architecture provides the option to draw on hydrogen production methods considered largely incompatible with the decentralised system. These would include coal gasification and nuclear thermal hydrogen generation. This vision of a hydrogen infrastructure depends on the development of a broader more dedicated hydrogen infrastructure including pipelines and distribution networks creating *"hydrogen corridors"* (McDowall & Eames 2006). The centralised architecture is the infrastructure vision that is likely to raise concerns over economic viability and timeframe for the realisation of a hydrogen economy. This is because of the need to change the existing infrastructure for electricity to support hydrogen. A centralised hydrogen infrastructure could require development of pipelines for carrying hydrogen around the country and distribution centres for storing and distributing hydrogen to end-users.

From the literature, it can be observed that views about the strengths and limitations of a hydrogen future have not changed notably over time. McDowall & Eames (2006) present a systematic review of the hydrogen futures literature at that time, based on studies published between 1996 and 2004. They identify both drivers for a hydrogen economy and the barriers and challenges. The drivers are split into four categories: climate change, energy security, localised air quality and competitiveness. The barriers and challenges are the likely absence of a hydrogen refuelling infrastructure, high costs associated with fuel cells, low carbon hydrogen production, and technological immaturity of hydrogen technologies.

Since its conception over forty years ago, the prospects for a hydrogen economy have evolved with developments in scientific research and understanding the causes of anthropogenic climate change. Hultman & Yaras (2012) suggest that a hydrogen economy would combine the pursuit of economic growth with environmental concerns and security of energy supply. Environmental concerns (Blanchette 2008; Hultman & Yara 2012; Brey *et al.* 2006) usually include climate change and associated green house gas emissions, and more localised air pollution (McDowall & Eames 2006; Hetland & Mulder 2007; Hajimaragha *et al.* 2011). Andrews & Shabani (2012) go one step further in their 2012 paper to include the energy needed to maintain supplies of clean water in the future.

Blanchette (2008) also describes the need for energy equality in situations where poorer individuals in parts of the developing world spend a disproportionate amount of time and money acquiring fuel. More recently Andrews & Shabani (2012) cite the three pronged threat of irreversible climate change, a deficit between oil demand and supply, and a rising levels of pollution generally as drivers for the hydrogen economy. Barriers are related to lack of technological maturity, infrastructure and the costs associated with both of the aforementioned (Andrews & Shabani 2012). The table below lists the drivers and barriers identified in the literature.

Table 2.2 The drivers and barriers to a hydrogen based energy system in the future as identified in the literature (Blanchette 2008; Murray *et al*. 2008 Hultman & Yara 2012; Brey *et al.* 2006).

Drivers for a hydrogen based energy system	Barriers to a hydrogen based energy system
Localised air pollution	Lack of technological maturity
Green house gas emissions	Existing infrastructure/cost of new infrastructure.
Economic growth through technological advancement	Financial implications of changing the incumbent system.
Competitiveness	
Energy security and supply	

Table 2.2 shows that the drivers and barriers presented in the hydrogen futures literature published after (McDowall & Eames 2006) have not changed and the strengths and limitations of transitioning to a hydrogen based energy system in the future remain the same.

2.3.3 Hydrogen futures: studies from outside the UK

The evidence from the literature cited below suggests that the hydrogen economy, as envisioned between 1996 and 2004 (the timeframe of studies considered in McDowall & Eames (2006)) and presented in Figure 2.1 (McDowall & Eames 2006), may not be suitable for current needs because more recent studies (Murray *et al*. 2008; Brey *et al*. 2006; Hetland and Mulder 2007) discuss the use of hydrogen as part of a larger low carbon energy system. This is a move away from the broader concept of a hydrogen economy and suggests that hydrogen is one of many low carbon energy options available now and into a low carbon future.

We now turn to some studies conducted in Poland, Norway and Spain since 2004 to identify how a transition to a hydrogen economy may occur (Murray *et al*. 2008; Brey *et al*. 2006; Hetland & Mulder 2007). As previously stated, the drivers for these particular investigations being reviewed are to ensure energy security and supply along with addressing a decaying environment and anxieties over localised air pollution.

In Poland, Murray *et al.* (2008) review the existing Polish energy system, resources, policies and measures from the perspective of planning a transition to a hydrogen economy. Their article recognises the importance of building alliances between stakeholders with different expertise, particularly in the mining and chemical industries where a hydrogen based future is seen to have a revitalising effect and is not restricted to the energy sector. A series of possible pathways to a hydrogen based future are presented. In these pathways the stakeholders involved in the investigation lean towards a coal based future. This builds on Poland's past dependence on its considerable coal resources. However, a diverse selection of feedstocks for hydrogen production was selected by the investigators, even if this was not considered the likely energy future in Poland. These included not only lignite and hard coal, but also natural gas, biomass using steam methane reforming, and onshore and offshore wind for electrolysis.

The majority of the hydrogen produced would be for the vehicle fuel cell market, with the possibility of further use in combined heat and power (CHP). Murray *et al.* (2008) concluded that the current infrastructure in Poland is very *limited* for hydrogen and that, although the country still has significant domestic fossil fuel reserves, further capacity for hydrogen should be developed. Barriers to the transition to a hydrogen economy in Poland were seen as primarily relating to a lack of likely end-use demand for hydrogen; it is thought unlikely that hydrogen production will increase without this (Murray *et al.* 2008).

In Norway, the concern of the Hetland & Mulder (2007) investigation was to understand how a large-scale transition to hydrogen might affect primary energy demand and greenhouse gas emissions. In this article, the authors begin to address the question as to why a hydrogen transition constitutes a better alternative than existing options. They argue that some hydrogen energy visions lack a critical approach and note that, although hydrogen appears low carbon at the end-use, energy must be put in to the system in order to get hydrogen out. Initially, this paper appears to be tackling the issue of *"green hydrogen"* (hydrogen produced from sustainable sources) verses *"brown hydrogen"* (hydrogen produced from fossil fuels). However, this is not the case because the paper suggests that the solution to reducing the environmental impact of hydrogen production from fossil fuels is to use carbon capture and storage. While in the short term this may reduce carbon dioxide emissions, it does not resolve questions over sustainable feedstocks for the production of hydrogen. Hetland & Mulder (2007) shows that there is some confusion about what makes hydrogen production either renewable or environmentally friendly. From the study, the reader could be confused because the authors are investigating the use of 'green hydrogen', a subject not well accounted for in the hydrogen futures literature, when in fact they are referring to 'brown hydrogen' with carbon capture and storage.

The sustainable production of hydrogen from renewable or sustainable sources may be considered a challenge due to the cost and infrastructure limitations identified in Table 2.1. The reduction of GHG emissions in end use technologies fed by hydrogen is well documented. It could be argued that producing hydrogen for use as a fuel from hydrocarbons is not renewable or environmentally friendly because of the continued use of virgin hydrocarbons creating GHG emissions and depleting the Earth's resources. The fossil fuel hydrocarbons could be used directly for fuel without increasing the energy requirements to convert fossil fuels into hydrogen. Hetland & Mulder (2007) conclude that although hydrogen presents itself as a potential fuel, especially in the transport sector, it may not become the obvious choice in Norway. This reasoning is based on cost and the efforts required to commercialise hydrogen, and uncertainty regarding the awaited fuel-cell vehicles and resolution of hydrogen storage problems (Hetland & Mulder 2007).

Brey *et al.* (2006) aim to explore design of a gradual transition to a hydrogen economy in Spain. Driven by concerns over energy dependency on fossil fuels and the gradual decay of the environment in Spain, they investigate the model of the hydrogen economy as one possible solution to these problems. Their paper analyses the possibilities of supplying 5, 10 and 15% of energy demand for transport using hydrogen produced from renewable resources. Identified as possible hydrogen production processes are photovoltaic energy with electrolysis, wind power with electrolysis, minihydraulic power with electrolysis, high temperature thermal solar with reforming and finally biomass with gasification. These were evaluated against different criteria, including cost, energetic performances and environmental equity. The paper concludes that, at the time of writing, the Spanish regions investigated could be self-sufficient in supplying their estimated energy demand for hydrogen; to achieve this, the government would need to promote renewable technologies across Spain significantly more rapidly than currently (Brey *et al.* 2006).

In this section, further investigations into the transition to a hydrogen based future have been considered. Hultman and Yaras (2012) have stated that the expectations for our hydrogen future have lowered, raising the following question: Why continue to investigate possibilities for a hydrogen based energy system in the future? To understand this situation further and, as suggested by Chatham House (2009), the technologies available must be fully understood. Further to this, it may be useful to understand whether investigating the technologies individually may improve technological deployment for hydrogen. Additionally, investigations into particular hydrogen production technologies and end users may see the position for hydrogen change.

The literature has described a shift from investigations that consider hydrogen as a complete energy concept where it is the primary energy vector to a position where hydrogen fuelled products and services are part of a low carbon energy system. The lowering of expectations around the likelihood of the hydrogen economy concept may begin to provide an explanation for the hypothesis presented in Chapter 1 of this thesis: *that, although the arguments for hydrogen as a fuel have not changed over the last twenty years and despite all the technological advancement and research in the field, it is no closer to commercialisation*. This is evidenced by Andrews & Shabani (2012) and McDowall & Eames (2006) who provide similar drivers and expectations, as well as concerns from the literature over technological risk and difficulties creating a supporting infrastructure. The result could be a situation where hydrogen technologies have not progressed due to risk, and concern of immature technologies and infrastructure developments outweighing the proposed benefits.

The following section covers the technical literature for hydrogen from waste.

2.4 The sustainable production of hydrogen from waste with a view to developing a technological innovation system

In this section, the technical literature for the sustainable production of hydrogen from waste will be reviewed. The review will aim to understand whether investigators working across the socio-technical spectrum of hydrogen production from waste identify similar opportunities, drivers, barriers and challenges for these technologies as part of a larger low carbon energy system.

As identified in section 2.3, the transition to a hydrogen economy is a complex multi-faceted process. The hydrogen futures literature describes technological immaturity and associated costs, as shown in Table 2.1, as a barrier to inserting hydrogen into a transition to a low carbon energy system. This section of the review aims to establish if this is the case across the hydrogen from waste literature.

Technological advancement, and in particular the production of hydrogen from wast,e is one possible component of the overall hydrogen economy concept. The use of waste as feedstock to create hydrogen is not well documented in the hydrogen futures literature. Often, waste and waste management processes as an option for hydrogen production amounts only to a brief reference in hydrogen economy or futures papers (Balat 2008; Balat & Kirtay 2010). Hydrogen production techniques are, however, supported by a broad technical literature and this includes how hydrogen can be produced from waste in several different ways. The literature includes experimentation using different feedstocks, processes and production possibilities with associated process efficiencies. The analysis of this literature presents an opportunity to establish the different drivers for hydrogen production from waste research globally and whether these drivers differ between countries. It may provide insight into the selection of feedstocks and their effectiveness along with the technologies showing greatest potential.

In this section, fourteen selected technical papers are reviewed to evaluate the current situation for hydrogen production from waste methods. The review does not critique the production methods themselves, but the supporting systems as described in the selection attributes in section 2.4.1.

Figure 2.2 shows a flow diagram of the possible routes to hydrogen through waste management systems. The diagram was derived based on information obtained in the literature for hydrogen production from waste techniques, including the waste management processes. This is by no means an exhaustive set of possibilities: the Figure aims to provide a visual interpretation of some of the key options.

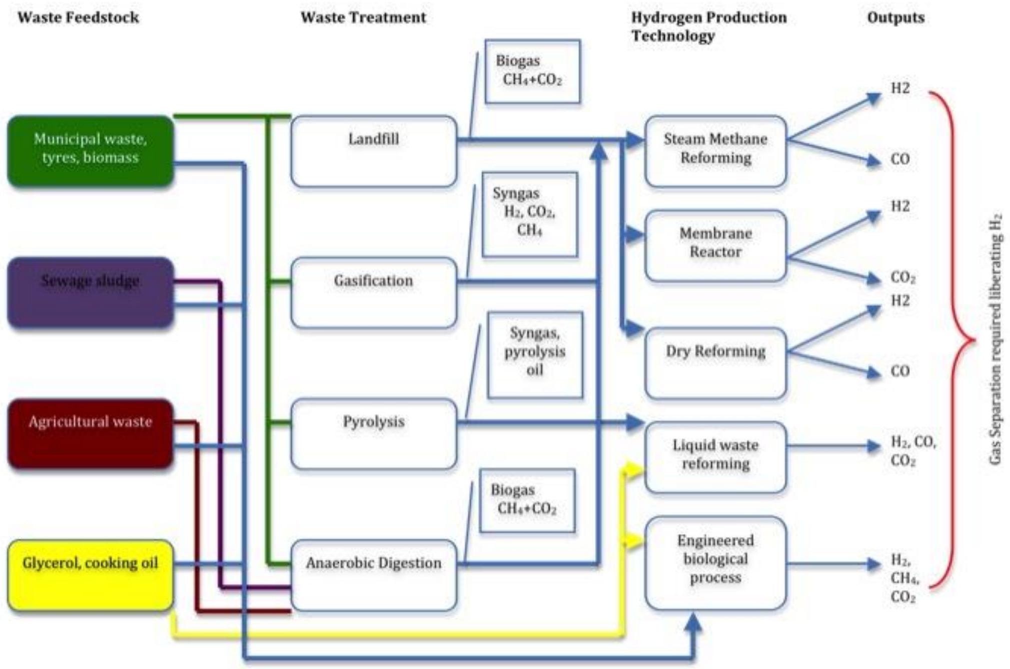


Figure 2.2. Possible routes to hydrogen through waste management processes.

2.4.1 Technical review attributes

A database search of the academic literature for “hydrogen from waste” and “hydrogen production from waste” was carried out using the Elsevier Science Direct website. The studies were chosen based on those that identified the particular use of waste feedstocks and technologies, as shown in Figure 2.2. The publications range in date from 2006 to 2012. The dates were chosen, firstly with the aim of keeping the literature as recent as possible; and, secondly, as a number of papers retrieved in the searches had been carefully reviewed as part of the McDowall and Eames (2006) paper. Prior to 2000, there were few papers that discussed specifically the production of hydrogen from waste. Therefore, it was felt that 2006 was an appropriate date to start the searches.

In order to usefully review the technical literature and establish their position within the broader hydrogen futures literature, the studies were reviewed through the examination of five questions. The questions were selected in order to establish information that is closely related to innovation systems (criteria 1, 2 and 5 below) and the sustainable production of hydrogen from waste (criteria 3 and 4 below). These questions are as follows.

1. Where the research is carried out, in what country? This is presented in section 2.4.1.1.
2. What are the drivers for this research and how have they been articulated in this technical literature? This is presented in section 2.4.1.2.
3. What waste feedstocks are discussed and what potential promise do these feedstocks offer? This is presented in section 2.4.1.1.
4. Which processes are being used to extract the hydrogen from the waste feedstocks, for example, is it steam methane reforming or microbial digestion? This is presented in section 2.4.1.1.
5. Finally, what kinds of outputs are being shared from this literature and what further research is suggested? This is presented in section 2.4.1.3.

2.4.1.1 International research into hydrogen production from wastes

The literature that addresses Questions 1, 2 and 5 above fits neatly into two distinct regional groups (see Question 1). The first is the Far East, including: Japan, Taiwan, Korea, China and Malaysia (Kim & Shin 2008; Kobayashi 2012; Kim *et al.* 2011; Cheng *et al.* 2012; Li *et al.* 2009; Li *et al.* 2011; Li *et al.* 2012; Ng *et al.* 2012). The second is the European countries including: France, Spain Denmark, UK, Romania and Italy (Luo *et al.*

2011; La Licata *et al.* 2011; Cormos 2012; Elbaba *et al.* 2011; Gómez *et al.* 2006; Guo *et al.* 2010).

Across the Far East countries, the feedstocks (Question 3) that are being researched are often related to waste food. This is described as the most abundant and problematic of the solid wastes (Kim & Shin 2008) that could be used for hydrogen production. Two sources of food wastes are being considered: 1) from cafeterias and 2) from municipal facilities (Kim & Shin 2008; Kobayashi *et al.* 2012). Other feedstocks being investigated include farm wastes, such as mushroom waste and agricultural waste-water (Li *et al*. 2011; Li *et al.* 2012) and molasses and cornstalks (Cheng *et al.* 2012). Finally, there are also two studies investigating the use of palm oil wastes as a feedstock. The use of this feedstock is controversial because concerns have been raised that the clearing of land for palm oil plantations is endangering the last habitats of some species (Li *et al.* 2009; Ng *et al.* 2012). However, for the countries considering palm oil as a feedstock, namely Malaysia and China, the plantations are an important part of their national income. Global demands on palm oil in the future will have a significant impact on the levels of palm oil wastes and the need to utilise them for hydrogen production (Li *et al.* 2009; Ng *et al.* 2012) preventing GHG emissions from large amounts of waste.

Across Europe, in contrast, there is a greater focus on other wastes that are often considered difficult to manage, for example waste tyres, rapeseed cake and glycerol from the biodiesel industry and coal, lignite, and biomass mixed with municipal solid wastes (Elbaba *et al.* 2011; Luo *et al.* 2011; Cormos 2012). This slightly different focus may be due to reasonably well-managed waste systems across Europe—in comparison to those of the Far East. The other three European studies use agricultural wastes, including slaughterhouse waste, as well as municipal waste-water and fruit and vegetable waste (Gomez *et al.* 2006; Guo *et al.* 2010; La Licata 2011).

In terms of processes (Question 4), by far the most popular techniques being investigated in these experimental studies are fermentation processes, particularly dark fermentation (Gómez *et al.* 2006; Guo *et al.* 2010; Kim *et al.* 2011; Luo *et al.* 2011;

La Licata *et al.* 2011; Li *et al.* 2012; Kobayashi *et al.* 2012). Fermentation processes, include both dark fermentation, anaerobic digestion (Kim & Shin 2008) and acid fermentation (Cheng *et al.* 2012). This popularity of fermentation techniques is the case in both the Far East and Europe. Dark fermentation for the production of hydrogen is a relatively new process (Gómez *et al.* 2006) and the literature demonstrates that interest in the hydrogen production possibilities continues to grow.

Anaerobic digestion is a process that is considered to provide a number of environmental benefits. It can provide a waste management process that deals with organic wastes, including food, agricultural, animal and water wastes and from these produce a useful gas product. The gas can then be used to produce hydrogen or utilised as methane (Lui 2008). The anaerobic digestion processes include hydrolysis/acidogenesis and methanogenesis. The following extract (in italics) and Figure 2.3 are taken from Lui (2008), a PhD thesis dedicated to the production of hydrogen from waste and waste residues using the dark fermentation process. Figure 2.3 provides a flowchart representation of the two-stage processes involved in creating bio-methane using anaerobic digestion processes.

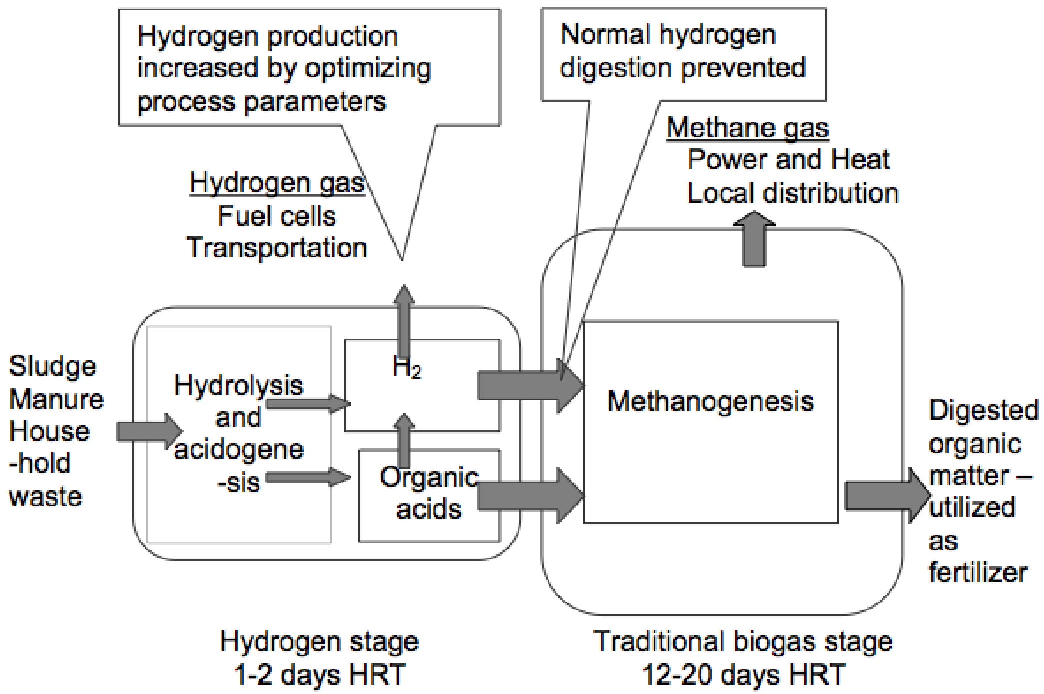


Figure 2.3 Bio-hydrogen production from waste using anaerobic digestion (from Lui 2008).

"Hydrolysis and acidogenesis produce hydrogen gas and organic acids, which can be further used to produce methane in methanogenesis. The hydrogen production step requires 1-2 days hydraulic retention time (HRT) and the methane production step requires longer HRT (12-20 days). If hydrogen gas is not harvested and further used for methane production, it is called a one-stage fermentation process. Otherwise it is called a two-stage fermentation process" (Lui 2008). It is accepted that anaerobic digestion can be severely affected by environmental factors such as pH, temperature and HRT (Lui 2008). These are all factors that influence the production of hydrogen from fermentation processes and researchers are seeking to improve the technologies. Addressing these issues will make the production of bio-hydrogen more economical (Guo *et al.* 2010).

Dark fermentation, or dark hydrogen fermentation as it is sometimes known, is a form of anaerobic digestion. In anaerobic conditions, hydrogen is produced from the gases created during the breakdown of organic compounds by the microorganisms. When organic compounds make up the only carbon and energy source for providing metabolic energy, the process is termed dark hydrogen fermentation (Lui 2008). Additionally, it differs from anaerobic digestion processes as the gas produced from the processes contains mostly hydrogen and carbon dioxide (Lui 2008), reducing the need for additional processes to liberate the hydrogen. Other possible components of the gas produced are methane, carbon monoxide and hydrogen sulphide; the gas mixture produced is dependent on the feedstock (Lui 2008) and the hydrogen-producing bacteria used in the fermentation process. Reducing these additional chemical compounds and increasing the hydrogen yield are all part of the scope of these recent studies (La Licata *et al.* 2011; Luo *et al.* 2011).

Earlier studies concerning dark fermentation of waste feedstocks have focused on simple sugars and less complex waste (Guo *et al.* 2010). These latest investigations into waste management and hydrogen production through dark fermentation are beginning to look at more complex wastes, including municipal solid waste. This process is beginning to be considered as the most environmentally friendly and potentially promising method for constantly recovering hydrogen fuel. The process is being demonstrated by an increasing number of successful trials producing relatively high hydrogen yields (Kobayashi *et al.* 2012)

At this time, there are no commercial bio-hydrogen plants producing hydrogen through dark fermentation because the process is not considered economically viable (Lui 2008). Reducing the costs of feedstocks for dark fermentation is one challenge facing researchers in the field and the investigation of dark fermentation using more abundant feedstocks such as food waste, unsold fruit and vegetables and palm oil wastes is part of the action being undertaken globally to address this (Kim *et al.* 2011; Li *et al.* 2012).

The remaining technical papers reviewed here are studies involving the gasification and steam methane reforming of wastes, with one study examining acid hydrolysis (Li *et al.* 2009; Cormos 2012; Elbaba *et al.* 2011; Li *et al.* 2011).

Gasification is a well-known technology that converts carbon-containing materials, including waste and biomass into useful products, such as chemicals, fuels and fertilisers. Gasification is not a combustion process: it uses little or no oxygen or air in a closed reactor plus heat to convert the carbon based feedstocks into a syngas. The carbon-based materials are easily broken down in the gasifier, thus allowing easy removal of contaminants, such as nitrogen, sulphur and mercury. The process of gasification has been used successfully to extract energy from wastes, converting the waste into valuable products and subsequently reducing the need for incineration and landfill (Gasification Technologies Council 2013).

Gasification is seen as a potentially good solution to managing wastes and extracting valuable commodities from waste. This reuse of the value in waste fits with concepts of sustainability and the recovery of wastes. Figure 2.4 provides an example of the gasification process for managing wastes.

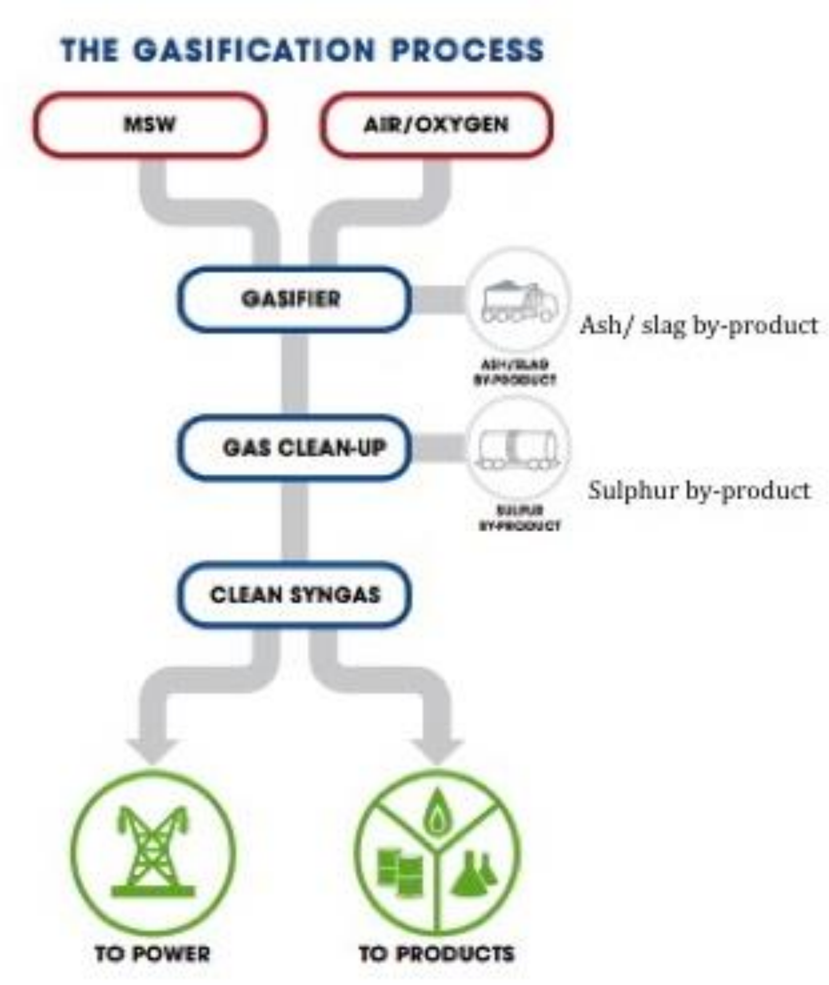


Figure 2.4. Example of gasification from waste process (from Gasification Technologies Council 2011).

The final paper in this technical review investigates hydrogen production from mushroom farm waste with a two-step acid hydrolysis process (Li *et al*. 2011). Acid hydrolysis is another form of fermentation that uses dilute acids (usually sulphuric, hydrochloric or nitric acid) to convert biomass into ethanol (C_2H_6O). The hydrolysed ethanol is then fermented, further liberating the hydrogen—this is known as two step hydrolysis (Li *et al.* 2011).

In this section, the literature has shown that dark fermentation is the most popular technology under investigation. This suggests that the technology has potential for commercialisation in the future for the production of hydrogen from waste. However, the technical literature does not provide an indication of when this technology may become commercialised. The evidence from these studies is that many different wastes offer potential feedstocks for hydrogen production. The majority of these are organic in nature including food and farm wastes. These types of wastes are readily available globally and in the UK on which this thesis is focused. From these studies, it has been possible to establish that the technologies exist to produce hydrogen from waste. The relevant technologies are at variable levels of maturity. This indicates that hydrogen produced from waste does have the potential articulated in the hydrogen futures literature and the policy landscape presented earlier in this chapter. However, the realisation of this potential clearly faces several challenges to be explored later in this thesis.

Recommendations for future research might be expected to provide a useful insight into the maturity stages of technologies. Each of the studies reviewed here contributed further knowledge to the technologies for the production of hydrogen from waste. However, perhaps surprisingly, only two made clear suggestions for future research. The suggested areas are: optimisation of the membranes used in dark fermentation processes (Kim *et al*. 2011); and improved understanding of the impact of the substrate composition on bio-hydrogen performance in dark fermentation (Guo *et al*. 2010). No definitive conclusion can be drawn from this due to the small number of studies with the suggestions. However, Lui (2008) states that there are currently no commercially producing bio-hydrogen plants using dark fermentation. This is due to the economics of the feedstock and processes currently used (Lui 2008) and may be one reason further research is suggested into dark fermentation processes.

2.4.1.2 Drivers for hydrogen production from waste research

It is clear from the papers reviewed in this section that the main drivers for the research into the production of hydrogen from waste are particularly related to the deterioration of the environment, both local and global—as discussed in the hydrogen futures section 2.3. This is the opening preamble presented in many of the technical papers, where production from waste is described in the following ways as: necessary for environmental protection and climate change (Guo *et al* .2010; Cormos 2012); required to tackle environmental problems, such as waste (Elbaba *et al.* 2011); to create a reduction of environmental pollutants (Luo *et al.* 2011; Cheng *et al.* 2012); needed to reduce global warming (Li *et al.* 2012); necessary to reduce greenhouse gas emissions and manage wastes (Kim & Shin 2008). In all other publications, the production of hydrogen from wastes is described as a good alternative to fossil fuels or providing an option that reduces reliance on fossil fuels (Gomez *et al*. 2006; Li *et al.* 2009; Li *et al.* 2011; La Licata *et al*. 2011; Kim *et al.* 2011; Kobayshi *et al.* 2012; Ng *et al*. 2012;).

The drivers for conducting research into technologies that produce hydrogen from waste reflect the drivers described in the hydrogen futures literature, reviewed in section 2.3. The need to source new feedstocks for energy to continue to support society globally whilst tackling concerns over environmental degradation and global climate change is evident in both the technology and futures literatures presented.

2.5 Sustainability transitions, transition management and the multi-level perspective

The hydrogen futures literature (section 2.3) presents the concept of transitioning to a hydrogen economy or low carbon future; this could be considered as a sustainability transition. The concept of sustainability transitions has a rich and diverse literature. Although this thesis does not fully explore sustainability transitions, it is important to recognise their relationship to innovation systems and particularly to the technological innovation systems discussed in section 2.6. Sustainability transitions consider many different types of transition, with energy being one of them. Sustainability transitions offer an alternative yet similar set of requirements to innovation systems in order, it could be argued, to meet the same low carbon goals. In addition to sustainability transitions, there are a number of other relevant theoretical approaches that have been used to explain transitions. These include: evolutionary economics, actor network theory, technology future studies and reflexive government (Markard *et al.* 2012). These theoretical approaches are not covered in detail in this thesis.

Markard *et al.* (2012) describe sustainability transitions as occurring in sectors like energy supply, water supply or transportation, and they can be conceptualised as socio-economic systems. These systems consist of actors and institutions as well as material artefacts and knowledge. It is acknowledged that transitions in these sectors from one existing paradigm to another generally occur over considerable time spans of fifty years or more (Markard *et al.* 2012).

Many scholars have created transition approaches that aim to provide some structure to these sustainability transitions. This includes the following: strategic niche management, transition management described in section 2.5.1, the multi level perspective described in section 2.5.2 innovation systems described in section 2.6, techno-economic paradigms and socio-metabolic transitions (Lachman 2013). The following two sections review two of these: i.e., transition management and the multi-level perspective.

2.5.1 Transition Management

Lachman (2013) describes transition management (TM) as a reflexive and participative governance concept that attempts to manage transformative change towards sustainable development by combining long term thinking with short term action. The key aspects of TM are the following (Lachman 2013).

- Experimenting and learning to guide variation and selection (learning-by-doing and doing-by-learning) while not chasing 'silver bullets' (keeping all options in consideration).
- Obtaining stakeholder input (from multiple levels) through inclusion and involvement.
- Complementing conventional policy with long term thinking, having the aim of sustainable development.
- Continuous reflection on all levels.
- Bringing system innovation alongside improvement

These key aspects of TM are carried out on three levels: strategic, tactical and operational.

The main criticisms of TM have been (Lachman 2013):

- Very difficult to apply in practice.
- The current literature focuses on the management of niche regimes, rather than the transition.
- Influences within the transition itself are not fully considered.
- Barriers and blocking mechanisms are not addressed within the system.
- There is a lack of tools to fully implement TM in policy making.

These criticisms are not dissimilar to those of MLP given in section 2.5.2 and functions of innovation 2.6.2. This suggests that the creation of a conceptual tool that replicates the relationships, influences and policy decisions involved in technology and sustainability transitions may be very difficult to achieve successfully.

2.5.2 Multi-level perspective (MLP) on socio-technical transitions

The multi-level perspective (MLP) was developed by Geels (2002)—see also earlier work by Rip & Kemp (1998) and further refined and applied by Geels & Schot (2007) and discussed in numerous other papers. In a recent paper that responded to criticisms, (Geels 2011) describes it as "theory that conceptualises overall dynamic patterns in socio-technical transitions", and combines concepts from evolutionary economics, science and technology studies, structuration theory and neo-institutional theory. Geels distinguishes three levels of heuristics making up the MLP. These are niche innovations, socio-technical regimes and socio-technical landscape (Geels & Schot 2007; Geels 2011).

This model of MLP for transitions is represented visually in Figure 2.5. The niche innovation represents the micro-level or local level of innovation. Niches are commonly referred to as 'protected spaces' or 'incubation rooms' for technologies (Markard and Truffer 2008). The socio-technical regime is the meso-level of the MLP and is the rule set or understandings that bind the technological knowledge. At this level of the MLP, the rule set is generated by production process technologies, engineering practices, policy makers and other interested stakeholders. The socio-technical regime is considered not to change (represented by 'dynamic stability' as shown in Figure 2.5) and it is at this level that comparisons to innovation systems can be made (Markard and Truffer 2008). The third level of the MLP is the macro-level represented by the socio-technical landscape. This is the external environment that influences both the regimes and niches; this may be factors including environmental problems, oil prices, economic growth, coalitions or cultural values.

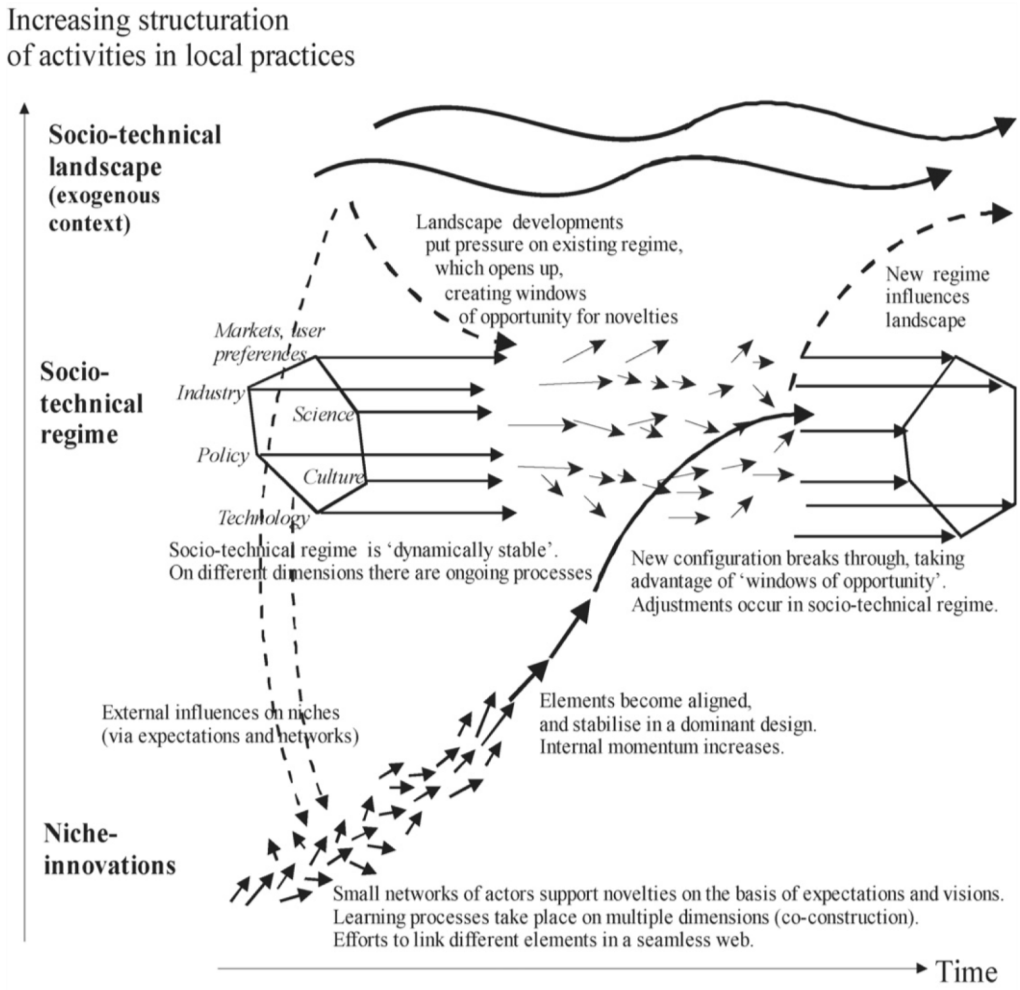


Figure 2.5. Multi-level perspective model for transitions (Geels & Schot 2007).

The model schematically illustrated in Figure 2.5 represents a theoretical concept visualising the process of an innovation's journey towards creating a new technological or societal paradigm—for example, a low carbon future through low carbon energy technologies. According to Markard and Truffer (2008) defining and delineating the socio-technical regime for an MLP application is challenging and may not be suitable in many empirical cases. This leads to the socio-technical regime being poorly reported in many MLP analyses. However they conclude that there is no unambiguous regime definition and that regimes may be defined at different levels of the model (Markard & Truffer 2008). The visual interpretation of the model in Figure 2.5 shows the complexities of the MLP. Further issues related to defining socio-technical regimes would create challenges for inexperienced practitioners to successfully analyse a transitional system using this model.

Genus & Coles (2008) in their review of MLP "*Rethinking the multi level perspective of technological transitions"* describe a number of criticisms of the MLP model for assessing technological transitions. These reinforce the challenges of defining the socio-technical regimes as described above and include concerns that, in some cases, the MLP model may be applied unsystematically. Further concerns relate to the timeframe of transitions and that they are often monitored after they have occurred. Genus & Coles (2008) also describe the value of agency and politics in technological transitions and suggest that the MLP does not sufficiently address these issues.

Further to Genus & Coles (2008), in their review paper, Smith *et al*. (2010) raise five key challenges relating to the MLP in terms of sustainable transitions. These are:

- relations between the conceptual levels of niche, regime and landscape;
- plural regimes and niches in interaction;
- the geography of transitions;
- empirical operationalisation of concepts; and
- governing regime transitions.

These five challenges add further credence to the idea that the current system models for monitoring sustainable technological transitions are not delivering the depth and detail of analysis required.

These criticisms raised by (Genus & Coles 2008) and (Smith *et al.* 2010) provide evidence that the MLP model does not deliver a sufficient system to measure an active technological transition considering all relationships between actors and institutions involved in a non-linear fashion. In response to this, Geels (2011) acknowledges the criticisms and describes the reasons behind why he thinks they have occurred:

- a lack of agency,
- operationalisation of regimes,
- bias towards bottom-up change models,
- epistemology and explanatory style,
- methodology,
- socio-technical landscape as residual category, and
- the differences between flat ontologies and hierarchical levels

The criticisms raised of the MLP and the responses strengthen the argument that many conceptual models for technology transitions are understood differently by different scholars, creating confusion in their application. This is discussed further in section 2.6.2 on functions of innovation.

2.6 Innovation Systems: technological innovation systems and functions of innovation

The literature provides many examples where technologies for hydrogen production from waste are being developed and researched to improve efficiency, processes and applications. In addition to developing such technologies, understanding the possible pathways of these technologies to reduce GHG emissions is also being researched and promoted by governments (DECC 2011; DECC 2012). Having a low carbon technology is, in itself, not sufficient to resolve societal concerns or meet government policies. The technology is part of a larger system where investment, market development, public support and legitimation of the technology take place.

The galvanising of these factors around a technology creates further development, diffusion and commercialisation of that technology and is known as the innovation system (Bergek *et al.* 2008). The move towards understanding technology and society and how we innovate within business, academia and government has resulted in the development and application of this concept. An innovation system is the conceptual system where interactions between the state, academia and business occur and move an innovation through diffusion and deployment. There is a growing body of literature that addresses the process of innovation and innovation systems at the national, regional and sectoral level (Metcalfe & Ramlogan 2008; Truffer *et al*. 2012). The innovation system itself is full of different functions and relationships that further the possibilities of an emerging technology or group of technologies in one field to meet societal needs.

From this review, it is proposed that there may be opportunities through further research to contribute improvements and develop knowledge further in several areas of the hydrogen futures literature. Further research, with particular focus on approaching the difficulties associated with diffusion and commercialisation of hydrogen technologies from within the innovation system and from the perspective of the experts involved, could assist with deployment of technologies

In recent years, there has been a rapid expansion in the studies of innovation and the way new technologies interact with society and move society towards a more sustainable future (Boons & Lüdeke-Freund 2012). Truffer *et al*. (2012) state that from their beginning, many analyses of technological innovation systems were intended to inform policy.

Before it is possible to investigate the innovation system literature, it is first necessary to define what the innovation process is and how society understands innovation. The OECD presents an overall definition of innovation that can be applied to most sectors: "Innovation is an iterative process initiated by the perception of a new market and/or service opportunity for a technology based invention that leads to development, production and marketing tasks striving for the commercial success of the invention" (Garcia & Calantone 2002).

Baker (2002) suggests that there are three main types of innovation; these are process, product/service and strategy. It is also understood that innovations exhibit different levels of novelty and can be described on a scale from incremental to radical and sustaining to discontinuous. An innovation of a product can be as simple as a rebrand or a minor twist on an existing theme or technology: this is incremental. Alternatively, the product can be radically new, changing the marketplace, but it does not necessarily follow that the product will have an exceptional impact. It is here that the concepts of sustaining and discontinuous innovation decipher the level of impact an innovation may have. A sustaining innovation improves the performance of an established product or service; whereas, a discontinuous innovation brings to the market an innovation that will typically undermine the incumbent products or services (Baker 2002).

Establishing the typologies of innovations plays an important role in determining the boundaries of technological innovation systems. It enables decisions to be made based on the aim of new technologies and, in turn, can contribute to the overall expected outcomes of the innovation system.

Understanding the components and dynamics of the innovation system requires the system and its outcomes to be defined. Here, it is defined as, "the elements and relationships, which interact in the production, diffusion and use of new and economically useful knowledge" (Lundvall 1992). Recent research has also acknowledged the importance of analysing the systematic interplay between networks and institutions (Truffer *et al.* 2012). Further to the developing of an understanding of this interplay, Truffer *et al*. (2012) suggest that future innovation system research needs to concentrate on the life cycle of the Technological Innovation System TIS, explained in more detail in the following paragraph. Of particular concern and interest to Truffer *et al.* (2012) are the dynamics that occur as a TIS develops from the embryonic phase into more mature structures with different system properties.

The term "national system of innovation" was first presented by Christopher Freeman in his book *Technology, Policy and Economic Performance* (Freeman 1987). Since that time, innovation systems have developed and evolved, looking at more detail within the national innovation system and exploring the concepts of regional and sectoral innovation systems. Further complementary approaches have been developed, including the technological and agricultural innovation system (forms of sectoral innovation systems), as well as the analyses of the functional dynamics within the innovation systems, which are termed “functions of innovation” (Johnson 1998, Foxon *et al*. 2005). These different levels and facets of innovation systems may also lend themselves to combinations, for example, regional agricultural or technological innovation systems.

Innovation systems and the role of sustainable innovation are considered necessary to create the conditions for society to adapt and make the transition to a low carbon future (Jacobsson & Bergek 2011). Sustainable innovation can be considered as the process of technical knowledge production through development of new products, technologies or organisation (Jinzhou 2011) that does not cause detriment to human and natural systems. The fostering of technological innovation particularly for ‘green’ technologies is considered as an important element of the build-up to sustainable development (Nill & Kemp 2009). These sustainable technological innovation systems require input from academia, business and government sectors in order to be effective tools for progress towards sustainable transitions.

When discussing agricultural innovation systems, Kelrkx *et al.* (2010) describe innovation systems as complex adaptive systems. These are self-organising systems whose properties can be analysed by studying their components separately (Kelrkx *et al.* 2010). This is likely to be the case for all sectoral innovation systems, including technological systems.

2.6.1 Technological innovation systems

The technological innovation system is often used to describe and analyse a new system for an emerging or niche technology that is not within the incumbent socio-technical paradigm (Kelrkx *et al.* 2010). The aim of the technological innovation system is to embed sustainable technologies, in this case for energy, into the incumbent system (Suurs *et al*. 2010).

Within a technological innovation system or TIS, there are a number of actors, institutions and technologies that act upon and interact with each other. These key players in the TIS are responsible for aligning themselves with each other and building up the processes around new technologies in order to promote a particular trajectory (Suurs *et al.* 2010). The detailed roles and actions of these actors, institutions and technologies are considered by the "functions of innovation" literature presented and examined in the following section 2.6.2.

Actors in the TIS are often organisations contributing to the advancement of the emerging technology, as a 'developer' or 'adapter', or indirectly, for example, as a 'regulator' or 'financier'. Suurs *et al.* (2010) make a further distinction: 'enactors' are actors that are directly involved in the development of a technology; whereas 'selectors' are actors that engage at a distance, for example, because they have the opportunity to choose between several different technologies. Institutions in the TIS refer to the laws, regulations, and expected technological norms. They can include more cognitive elements, such as 'rules of thumb' and shared expectations. Finally, technological factors are the artefacts and technological infrastructure in which the TIS is integrated. These include components such as, cost, safety, reliability and effects of scaling up (Suurs *et al.* 2010).

Prior to Suurs *et al.* (2010)'s presentation of the concept of the influence of cognitive elements in the innovation system, Doloreux & Parto (2005) described innovation as embedded in social relationships. These relationships are considered to develop over time and along culturally determined lines, particularly when considered in a regional and sometimes sectoral context. These cultural contexts can often provide sets of rules: i.e., conventions and expected behaviours that may all influence the interactions and mutual understanding during innovation system process, such as transmitting information and exchanging knowledge (Doloreux & Parto 2005). Therefore, the development and effectiveness of the relationships and interactions occurring within the innovation system become a critical part of the build-up to an effective and productive innovation system.

Commercialisation and acceptance of a technology into the incumbent system is often the desired outcome of a TIS. The technological innovation system deals with new, emerging and niche technologies with the aim, through developing relationships and interactions within the TIS, of creating a technology or group of technologies that are commercially viable. Suurs *et al.* (2010), for example, stress that emerging technologies pass through a formative phase before they reach market diffusion. A TIS in the formative stages is often characterised by continuous changes in technologies and weakly represented support from institutions and actors within the system (Suurs *et al.* 2010).

How this weak phase of the TIS is managed to further the technology and meet the requirements of society to address issues of energy security and GHG emissions has been the consideration of many publications. It is often suggested in the literature that governments should be able to identify faulty components in the system (Jacobsson & Bergek 2011) and work to create an environmental policy framework to account for environmental technological innovation (Nill & Kemp 2009).

Two broad approaches have been taken in the literature to understand the TIS in more detail and to progress emerging technologies in support of sustainable development. The first has been to describe theoretically the role of different actors and institutions within the TIS. The second, described in section 2.6.1, is to create a conceptual model that enables analyses of the different components of the TIS. These models have been applied to many renewable energy technologies in order to appraise the success and failure of the technologies, including policy and governance of TIS, functions of innovation approach, and geography of TIS (Truffer *et al*. 2012).

Discussion of the role of the government as an actor, particularly as policy maker, in innovation is common and has produced a wealth of literature (e.g., Foxon *et al*. 2005 Vergragt & Brown 2007; Metcalfe 2008; Nill & Kemp 2009; Nillson *et al.* 2012). Governments are considered as enabling actors within the innovation system through activities in research and development support, along with intervention in technological markets. Nilsson *et al.* (2012) describe three roles of government within the innovation system:

- The first in the role of preparing, deciding on and implementing measures to advance societal objectives.
- The second as a facilitator or co-ordinator of interactions between private and public actors.
- The third as good governors, being accountable, transparent and creating democratic legitimacy (Nilsson *et al.* 2012).

Requirements with respect to science, technology and innovation policy have been changing over recent years. Processes of innovation have become more interactive, distributed and complex, thus broadening the potential inroads for policy beyond simply science and technology (Weber 2006 p. 189). Nill & Kemp (2009) discuss the role of adaptive policy that can deal with the dynamics of variation, selection and retention of innovations. Where they suggest this adaptive approach has been successful is around policies based on strategic niche management, transition management and time strategies (Nill & Kemp 2009). This kind of approach may also be known as 'reflexive governance'.

The policy landscape presented in Chapter 1 provides some insight into the language used to communicate government policies. Expressions such as adaptive policy, transition management and reflexive governance are not commonly used terms. However, their presence has increased over the past five years. In their paper discussing innovation in sustainable mobility, Vergragt & Brown (2007) conclude that the government have an important role to play through regulatory policies and strategic incentives and disincentives. The literature provides an accepted view that in terms of innovation, proactive action by government is essential to achieving successful outcomes.

Within the conceptual framework 'functions of innovation' developed to analyse the dynamics of the innovation system, there is a role for the government within each function and between functions. This will be described in more detail in section 2.6.2.

Within the technological innovation systems literature a further observation relating to societal learning and how culturally new technologies can become incumbent technologies is made by Johnson (1998). Two main types of learning associated with TIS have been described. Learning-by-doing is the process where technology developers learn by repeating an experiment or activity over and over and making gradual innovations to improve the technology. Learning-by-using is the process where technology innovators learn by the feedback from those using their products. Both are processes involving learning through the day-to-day interaction with technologies. In the first instance the need for technological advancement may be developed through learning that takes place through the use and interaction with incumbent technologies. For example, the burning of fossil fuels has resulted in air pollution and GHG emissions. Researchers have discovered the detrimental effects of these side effects of fossil fuels and are now seeking to make improvements to the current energy system in the form of low carbon technologies. It is in these learning phases that new problems associated with a technology may be identified or new regulations to manage a technology may be developed (Johnson 1998). The process of learning and sharing learning between actors within the TIS may be a critical behaviour to produce successful outcomes in both the short and the long term.

Jacobsson & Bergek (2011) suggest that the key contribution of innovation system analyses to the study of sustainability transitions is that they provide policy makers with a tool for identifying weaknesses. The technological innovations systems literature supports many conceptual frameworks and analytical tools that may provide assistance to policy makers when deciding on interventions for technological development. These frameworks and tools, with examples relating to renewable technologies, are described in the following section.

2.6.2 Conceptual models for technological innovation systems

Jacobsson & Bergek (2011) describe the scale of decarbonising the electricity sector as a formidable challenge. Global demand for electricity rose at a rate of 3.5% per annum from 1973 to 2008 to approximately 20,000TWh. Combining this with the persistent problem of the unsustainability of the automobile, responsible for local air pollution, GHG emissions, road congestion and noise (Vergragt & Brown 2007) and widespread fossil fuel for industrial and domestic heat, the scale of the decarbonisation challenge becomes even greater. The transformation agenda for reducing fossil fuel reliance across sectors involves developing, not only new technologies and infrastructures, but also building up the associated capital goods industries and supply chains. These are actions that could take decades to achieve (Jacobsson & Bergek 2011).

To try to gain perspective on how this transformation may happen and to inform policy-making, a number of technological innovation system models have been developed since the seminal paper of Carlsson and Stankiewicz (1991). These models, through different system approaches, aim to analyse the possible strengths and weakness of an innovation system and predict how these systems may impact upon technological development in a particular sector. In the 1990s, the focus of TIS was on a variety of different systems, some focusing on knowledge in a particular field, some on a particular technology or product. Others would direct their attention to the industrial sector or sectors where technologies were in their infancy (Truffer *et al*. 2012). The initial framework presented by Carlsson and Stankiewicz (1991) has, following these various investigations into TIS, seen several conceptual refinements. One of the most influential is the functions of innovation approach (Johnson and Jacobsson 2001) that identifies the requirements for a system to run smoothly (Truffer *et al.* 2012). Other conceptual contributions include the multi-level perspective described earlier in this chapter in section 2.5.

Energy has always been a topic prominent in the TIS and broader sustainability transitions literature (Truffer *et al.* 2012). The application of TIS conceptual frameworks to energy and sustainability issues is covered in section 2.6.2.1.

To begin this review of innovation system analyses, four different approaches are covered:

- Adaptive policy making for emerging technological paradigms
- ‘Build up’ (the growth of TIS activities from actors and institutions) of TIS focussing on networks

- Variation analysis
- Computer models for risk and effectiveness of technological systems

These approaches were chosen as they represent a non-functions approach to examining a TIS. This is to demonstrate how technological innovation systems are being considered, both using functions of innovation and without using the functions approach. In each case, they represent the assessment of the innovation system for environment, sustainability or energy innovation from a unique perspective.

Oltra & Saint Jean (2009) presented a framework for an integrated and dynamic analysis of environmental innovation policy and its effect on environmental innovation in the French automotive industry. The framework focussed on c*o-evolutionary or adaptive policy making* to adjust to emerging technological paradigms. The analysis used the framework that produced sectoral patterns of innovation. Their analysis revealed that technological regime and demand conditions lead to technological inertia and a strong persistence of the dominant design (Oltra & Saint Jean 2009). This shows that the design of the technological regime plays an important part in the success of new technological designs. The dominant design is the incumbent technology or system. For example, fossil fuel and nuclear-based technologies are currently dominant in the energy system in Europe.

Moving away from the policy focus and the role of governments, Musiolik *et al.* (2012) present a conceptual framework for analysing the *build up of a TIS* with a particular focus on the role of networks. Applying their framework through desk-based research to the technological field of stationary fuel cells, they identify that networks are used to create and shape innovation system resources. As the actors within the system collaborate in networks, they also establish network resources such as knowledge and financial resources. These may become crucial for the effectiveness of the network in the build up of the system. These networks can increase their reputations and be used to influence other key actors within the innovation system. Musiolik *et al.* (2012) summarised their analysis by stating that, although the contents of the networks developed were necessary in terms of system build up, these networks were not readily accessible and needed time to be developed.

Markard *et al.* (2009) present a concept for the identification and analysis of future development options using a *variation analysis* for biogas in Switzerland. This type of analysis aims to identify different socio-technical and organisational variants that may occur within a particular innovation system. Key characteristics of the variation analysis will include the following: actors and institutions, innovation, market aspects including current niches and technology diffusion, as well as environmental performance within the system. The researchers undertook a desk study to identify possible variations that may occur within the system. Using this method of discursive foresight processes, it is suggested that the results can be used to inform strategy for businesses and policy makers (Markard *et al.* 2009).

Finally, two different computer-modelling applications were reported by Wu *et al.* (2010) and Blazy *et al.* (2009), to explore the risks of technological innovation in China and effectiveness of technological innovation in Guadeloupe, respectively. Both groups simulated a number of possible scenarios based on selected criteria from the literature and from the field and produced results that supported decision-making. Wu et al. concluded that the simulation for evaluating risk produced results that were consistent with business and government practice. Blazy *et al.* reported that the results of the simulation demonstrated the importance of understanding clearly the context of where the innovation would be used. For example, in specific contexts some innovations led to environmental and production benefits, but this was not the case universally (Blazy *et al.* 2009; Wu *et al.* 2010).

These four approaches presented in the five studies represent uniquely different perspectives on technological innovation systems. However, one recurring feature across all the studies is that they are desk-based. In other words, they have not directly interacted with individuals, organisations or actors within the innovation system. In the cases of the first three studies (Oltra & Saint Jean 2009; Musiolik *et al.* 2012) presented, this suggests that that the roles of individuals or organisations and the interactions between them are not fully reflected in the analyses.

Two further strands of literature have developed featuring conceptual frameworks that are acknowledged as schemes of analysis for sustainable transitions and technological innovation systems. The first strand is the multi-level perspective discussed in section 2.5 and the second strand is the functions of innovation framework discussed in section 2.6.2.1. These strands of literature developed largely independently of each other, although they are explaining similar empirical phenomena (Markard & Truffer 2008)

2.6.2.1 Functions of innovation

The conceptual framework presented as the functions of innovations (FoI) has a less clear history than MLP. First descriptions of FoI are commonly considered to have been by Johnson (1998) in a Chalmers University publication, *Functions of Innovation Approach.* Looking further into the history of functions of innovation in the broader literature, evidence from the Massachusetts Institute of Technology suggests that the functions may have been first conceived by Roberts & Fusfeld (1980) as early as 1980. Here, they describe several critical functions for innovation: idea generating, entrepreneuring or championing, project leading, gatekeeping and sponsoring or coaching.

Johnson (1998) describes eight functions of innovation extrapolated from the literature on innovation systems at the time. These are as follows.

1. Supply incentives for companies to engage in innovative work.
2. Supply resources.
3. Guide the direction of the search.
4. Recognise the potential for growth of the innovation.
5. Facilitate the exchange of information and knowledge.
6. Stimulate and create markets.
7. Reduce social uncertainty.
8. Counteract the resistance to change.

In the empirical work that followed, Johnson (1998) initial list of 8 functions is reduced to 5 (Hekkert *et al.* 2007):

1. Create new knowledge.
2. Guide the direction of the search processes.
3. Supply resources.
4. Facilitate the creation of positive external economies (in the form of an exchange of information, knowledge and visions).
5. Facilitate the formation of markets.

The concept of the functions of innovation within technological innovation systems has continued to evolve over the past fifteen years, with two core sets of functions now broadly accepted. Presented in Table 2.3 are the functions of innovation as described by Hekkert *et al.* 2007 in the first column and Bergek *et al.* 2008 in the second column.

Table 2.3. Lists the two approaches to functions of innovation (Hekkert *et al*. 2007; Bergek *et al.* 2008).

Functions of Innovation Hekkert *et al*. 2007	Functions of Innovation Bergek *et al*. 2008
Entrepreneurial activities – the role of the entrepreneur is to turn the potential of new knowledge, networks and markets into concrete actions to generate and take advantage of new business opportunities.	**Knowledge development and diffusion** – this function captures the breadth and depth of the current knowledge base and how that changes over time, including how that knowledge is diffused and combined in the system.
Knowledge development – three typical indicators to map this function over time are research and development projects, patents and investments in research and development.	**Influence on the direction of the search** – For a technological innovation system to develop, organisations must choose to enter it. There must be sufficient incentives and/or pressures for organisations to be induced to do so.
Knowledge diffusion through networks – the exchange of information through networks. Information diffusion can support policy decisions ensuring they are consistent with the latest technological insights.	**Entrepreneurial experimentation** – This is an area where uncertainty in the TIS exists. It involves the probing into new technologies and applications where some will fail and some will succeed. This creates social learning and, without this experimentation, new technologies will stagnate.
Guidance of the search – where there is a choice of technological options, specific foci are chosen for further investment. Industry, the government and/or the market can fulfil this.	**Market Formation** – For an emerging TIS, a market place may not exist. Institutional change for example, the formation of standards or tax incentives are often a prerequisite for markets to evolve.
Market formation – creation of protected spaces for new technologies, temporary advantages for a new technology through tax regimes.	**Legitimation** – this is a matter of social acceptance and compliance with relevant institutions. New technologies need to be considered appropriate and desirable for relevant actors to mobilise resources.
Resources mobilisation – the allocation of sufficient resources is necessary to make knowledge production possible. This may be through funding for niche technology development by industry or government.	**Resource mobilisation** – as a technology evolves, a range of different resources need to be mobilised. This could be financial or human capital through education, capital investments, entrepreneurship and complementary products and services.
Creation of legitimacy/ counteract resistance to change – to become part of an incumbent regime, advocacy coalitions for a technology must lobby for resources and favourable tax regimes and create legitimacy for the new technology.	**Development of positive externalities** – the systemic nature of the innovation and diffusion suggests that the generation of positive external economies is a key process in the formation and growth of a TIS. The entry of new firms to the sector is key to this.

Although developed independently, both of the schemes of analysis for the functions of innovation in Table 2.1 are broadly similar. The functions in Table 2.1 are presented in the order in which they are presented by the authors. They both suggest seven core functions in order to achieve successful transitions to a new technology using technological innovation systems. Bergek *et al.* (2008), however, take the seven functions one step further by including the development of positive externalities associated with new entrants into the technological field and development of the supply chain. This function is not shown in the Hekkert *et al.* (2007) scheme of analysis but it finalises the success of the TIS through the entrance of new firms and organisations into the technological field.

In Truffer *et al*. (2012), the authors have complied a comprehensive table based on key processes involved in technological innovation system build-up. This is shown in Table 2.2 below and demonstrates how these different sets of functions can be brought together.

Table 2.4. Key processes in technological innovation build up (from Truffer *et al.* 2012).

Key process	Definition	Indicators
Knowledge creation and diffusion	Activities that create new knowledge, e.g. learning by searching, learning by doing; activities that lead to exchange of information among actors, learning by interacting and learning by using in networks	R&D projects, no. of involved actors, no. of workshops and conferences, network size and intensity, activities of industry associations, websites, conferences, linkages among key stakeholders
Influence on the direction of the search	Activities that positively affect the visibility of requirements of actors (users) and that have an influence on further investments in the technology	Targets set by the government, changes in regulatory frameworks, no. of press articles that raise expectations, visions and beliefs in growth potential
Entrepreneurial experimentation	Emergence and decline of active entrepreneurs as a prime indication of the performance of an innovation system, concrete activities to appropriate basic knowledge, to generate and realize business opportunities	No. of new entrants, no. of diversification activities of incumbents, no. of experiments
Market formation	Activities that contribute to the creation of demand or the provision of protected space for the new technology, e.g. construction of market segments	No. of niche markets, specific tax regimes and regulations, environmental standards
Creation of legitimacy	Activities that counteract resistance to change or improve taken-for-grantedness of new technologies	Rise and growth of interest groups and their lobbying activities
Resource mobilization	Activities related to the mobilization and allocation of basic inputs such as financial, material or human capital	Availability of competence/human capital, financial capital, complementary assets for key actors
Development of positive externalities	Outcomes of investments or of activities that cannot be fully appropriated by the investor, free resources that increase with number of entrants, emerge through firm co-location in TIS	Emergence of pooled labor markets, intermediate goods and service providers, information flows and knowledge spill-overs

Source: Compiled from (Bergek, Jacobsson, Carlsson, Lindmark, et al. 2008a; Hekkert, Suurs, Negro, Kuhlmann, et al. 2007; Musiolik and Markard 2011)

Many studies (Negro et al. 2007; Negro *et al.* 2008; Suurs *et al.* 2010; Hawkey 2012; Breukers *et al.* 2013) have been published using these schemes of analysis to understand the functional dynamics of the TIS in terms of various renewable technology fields, including: natural gas as automotive fuel, fuel cells, district heating, biomass, biomass gasification and biomass gasification. These studies cover identification of functions within their respective TIS and identify barriers and blocking mechanisms, as well as drivers for the TIS, but do not seek to investigate in detail the relationships and interactions between the different functions. Despite this, the recognition of their importance by Hekkert *et al.* (2007) and Bergek *et al.* (2008) is noted below.

From the studies reviewed using the functions of innovation schemes of analysis, only one Dutch study (Breukers *et al.* 2013) explored the technological innovation system using participatory methods. Breukers *et al.* (2013) use constructive conflict methodology to facilitate the articulation and confrontation of rival reviews relating to biomass in the Netherlands. This constructive conflict methodology is designed to create learning among dialogue participants and was successful in the study.

Both schemes by Hekkert *et al*. (2007) and Bergek *et al*. (2008) recognise that the functions influence each other and that the fulfilment of one function may influence the fulfilment of other functions. An example given by Hekkert *et al.* (2007) is that the function "guidance of the search" has positive effects on knowledge creation. At the same time, a certain amount of knowledge creation is necessary to create expectations about the new technology, which may eventually lead to the building up of legitimacy. They conclude that the TIS will present a non-linear model with multiple interactions between functions, which will either positively or negatively affect the overall performance of the system.

Truffer *et al*. (2012) have published a comprehensive review of energy innovation systems and suggestions for possible future research. Two key themes from this report are particularly relevant to this thesis. The first refers to the revisiting of the functions of innovation concept, where it is suggested that confusion may be generated as different scholars have different understanding of the terms used in the functions literature. Additionally Truffer *et al.* (2012) suggest that there is a need to reflect on the conceptual relationships between the TIS structures and the functions.

The second area of interest is the issue of the TIS life cycle. Truffer *et al.* (2012) state that scholars working with TIS approaches, not only functions of innovation, have not yet developed a conceptual framework that explicitly elaborates on the evolution of innovation systems over time. Understanding how a TIS needs to change to meet the demands of a maturing technology is a particular consideration of this thesis—explored in the experimental chapters 5, 6 and 7.

2.7 Research Gaps

The literature presents several gaps in the research on hydrogen from waste. This may be in part due to the multidisciplinary nature of the research field, which requires different academic fields to be brought together. It is not always possible to make these existing academic fields fit neatly together and to identify a clear pathway for this chosen research. This leads to a somewhat fragmented literature background. In this section, the research gaps considered of particular relevance to this thesis are identified. It is important to recognise that hydrogen production from waste presents one small element of the larger hydrogen production literature. While there is a significant body of literature exploring the technologies, there is a dearth of literature specific to the perspectives and innovation systems surrounding the hydrogen from waste field.

The policies presented in section 2.1 place significant importance on the efficacy of new technologies to reduce GHG emissions and help the UK government to meet its targets for renewable energies. The evidence from the literature shows that technologies for hydrogen production from waste are being advanced through technological research and development. There is less comprehension of the pathways that these technologies could take in order to be utilised and accepted as successful commercially-applicable low carbon technologies. As will be explained below, although the technological innovation systems literature demonstrates how conceptual models can be used to identify deficiencies within the system, very often these models are not comparable to 'real' situations. This lack of comparability may be a result of the model complexities, for example, the unclear status of relationships between parts of the model, or a misunderstanding or lack of appreciation of the role of actors, organisations and institutions within the system itself. It will be argued that this gap in the literature provides an opportunity to develop a bespoke model to investigate the technological innovation systems for hydrogen from waste. This will include systematically analysing the relationships and interactions between actors and institutions involved in the system for hydrogen production from waste across UK regions. The results will be presented in Chapter 5 and 6 and 7.

As we have seen, the innovation systems literature presents a number of models that can be used to analyse and map out TIS. These models often focus on the drivers, barriers and system failures, but do not focus in as much detail on the relationships and interactions occurring within the system. Therefore, it is suggested here that adapting and using appropriate parts of the conceptual frameworks and models presented in the technological innovation literature would allow for the development of a new prototype model. This model could be used for testing the likely efficacy of regional technological innovations systems in the UK with specific reference to hydrogen production from waste. This will be addressed in Chapter 5.

As suggested in section 2.5, the models presented in the technological innovation systems literature show a lack of participatory data input from stakeholders involved in the system. Qualitative and quantitative input into system analyses is often from desk study research, rather than engagement with actual or potential system actors, which means that the analysis of interactions between the actors and others elements is more conceptual than empirical. This suggests the value of conducting participatory technology and innovation system studies with key stakeholders for hydrogen production from waste, in order to analyse and better understand these interactions and the ongoing challenges faced by TIS. These research gaps will be addressed in Chapters 4, 6 and 7.

The policy landscape also provides an indication of the current insecurity felt towards the role and commercialisation of hydrogen technologies more generally. As noted in section 2.2, only a passing mention is given in most UK policies and strategies to hydrogen fuel cells, with those for London alone articulating the potential of hydrogen from waste within the energy system. This suggests a promising opportunity to investigate the role of the technological innovation system for hydrogen from waste. The subject will be addressed in Chapter 7.

2.8 Methods to address research gaps

Further literature reviews for possible methods to address the gaps in the literature are provided in Chapter 3, Methodology. Included are full literature reviews for the methods used in this thesis.

2.9 Conclusion

In this chapter, a selected set of relevant strands of literature has been analysed and critiqued. The literature reviewed included transitions to a low carbon future, hydrogen futures, and hydrogen from waste technologies and innovation systems. Each of the literature strands offers some contribution towards addressing the research questions presented and meeting the objective: *To analyse and discuss the extant literature germane to the development of technological innovation systems in the technological field of hydrogen production from waste.* The hydrogen futures literature shows that the drivers and blocking mechanisms relating to deployment of hydrogen technologies have remained largely unchanged over the forty years since the conception of the hydrogen economy. This literature review has identified the technological possibilities for creating hydrogen from waste, as well as discussing the different visions of a hydrogen future. This analysis of the literature helps to address the overarching research question:

What role might hydrogen from waste play in a future low carbon energy system in the UK?

The literature review has suggested that there is a space for examining the technological innovation system for hydrogen from waste using participatory methods to understand the relationships between the functions of innovation. The analysis of the literature on conceptual models used to examine TIS has shown that the current models are inadequate for a fully comprehensive analysis of real time transitions. This supports the potential value of addressing the sub-research questions:

- *What does the comparison (Aim 2) between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?,* and
- *How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?*

The methods identified as offering potential to address these questions are described in the next chapter.

2.10 References

Andrews J., Shabani B. Re-envisioning the role of hydrogen in a sustainable energy economy. International Journal of Hydrogen Energy. 37 (2012) 1184–1203

Baker A. Ch 14. (2002) Innovation Online Accessed 03/04/2013. http://www.au.af.mil/au/awc/awcgate/doe/benchmark/ch14.pdf

Balat H. Kirtay E. Hydrogen from biomass: Present scenario and future prospects. International Journal of Hydrogen Energy 35 (2010) 7416–7426

Balat M. Potential Importance of hydrogen as a future solution to environmental and transportation problems. International Journal of Hydrogen Energy 33 (2008) 4013–4029

Bergek A., Jacobsson S., Carlsson B., Lindmark S., Rickne A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (2008) 407–429

Blanchette S. Jr. A hydrogen economy and its impact on the world as we know it. Energy Policy 36 (2008) 522-530

Blazy J-M., dorel M., Salmon F., Ozier-Lafontaine H., Wery J., Tixier P. Model-based assessment if technological innovation in banana cropping systems contextualised by farm types in Guadeloupe. Europ. J. Agronomy 31 (2009) 10–19

Boons F., Lüdeke-Freund F. Business models for sustainable innovation: state-of-the-art and steps towards a research agenda. Article in Press Journal of Cleaner production (2012)

Breukers S., Hisschemöller M., Cuppen E., Suurs R. Analysing the past and exploring the future of sustainable biomass. Participatory stakeholder dialogue and technological innovation system research. Article in Press technological Forecasting and Social Change 2013

Brey J.J., Brey R., Carazo A.F., Contreras I., Hernándes-Díaz A.G., Gallardo V. Designing a gradual transition to a hydrogen economy in Spain. Journal of Power Sources 159 (2006) 1231–1240

Chatham House. Who Owns Our Low Carbon Future? Intellectual Property and Energy technologies. A Chatham House Report 2009.

Cormos C-C. Hydrogen and power co-generation based on coal and biomass/solid wastes co-gasification with carbon capture and storage. International Journal of Hydrogen Energy 37 (2012) 5637–5648

DECC 2011. UK Renewable Energy Roadmap. UK Government Publication.

DECC 2012. DECC Science and Innovation Strategy 2012. UK Government.

DEFRA 200. Waste Strategy England and Wales. Department for Environment, Transport and the Regions. UK Government Publication.

DEFRA 2007. Waste Strategy for England. Department for Environment Food and Rural Affairs. UK Government Publication.

DEFRA 2011. Anaerobic Digestion Strategy and Plan 2011. A commitment to increasing energy from waste through anaerobic digestion. Department of Energy and Climate Change; Department for Environment Food and Rural Affairs Publication.

DEFRA 2011. Waste Policy in England. Government Review and Action Plan 2011.

Defra Waste Policy 2011. Government Review of Waste Policy in England. Government Publication.

DOENI 2006. Towards Resource Management. Northern Ireland Waste Strategy 2006-2020. Department of Environment Northern Ireland.

Doloreux D., Parto S. Regional innovation systems: Current discourse and unresolved issues. Technology in Society 27 (2005) 133–153

Eames M., McDowall W. UKSHEC Hydrogen Visions. UK SHEC Social Science Working Paper No. 9. (2005)

EERE (2010) Energy Efficiency and Renewable Energy: Fuel cell technologies programme. US Department for Energy. EERE Information Centre.

Elbaba I.F., Wu C., Williams P.T. Hydrogen production from the pyrolysis—gasification of waste tyres with nickel/cerium catalyst. Interantional Journal of Hydrogen Energy 36 (2011) 6628–6637

European Commission 2011. A Roadmap for moving to a competitive low carbon economy in 2050 Online accessed 31/03/2013 (2011). Communication from the Commission to the European Parliament, the Council, The European and Social Committee and the Committee of the Regions.

European Parliament 1975. Waste Framework Directive 75/442/EC of the European Parliament on waste.

European Parliament 1991. Waste Framework Directive EC/156/EEC of the European Parliament on waste.

European Parliament 1999. Landfill Directive 1999/31/EC of the European Parliament on the Landfill of waste.

European Parliament 2008. Directive of the European Parliament 2008/98/EC on waste (Waste Framework Directive)

European Parliament 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

Foxon T., Gross R., Chase A., Howes J., Arnall A., Anderson D. UK innovation systems for new and renewable energy technologies: drivers, barriers and system failures. Energy Policy 33 (2005) 2123–2137

Foxon T., Pearson P. Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime. Journal of Cleaner Production (2008) S148–S161

Freeman C. Technology, Policy and Economic Performance. Lessons from Japan. Pinter Publishers. 1987.

Garcia R., Calantone R. A critical look at innovation typology and innovativeness terminology: a literature review. The Journal of Product Innovation Management 19 (2002) 110–132

Gasification Technologies Council 2011. Gasification – The Waste to Energy Solution. Gasification Technologies Council 2013 Fast Facts. Accessed 30/03/2013 online. http://www.gasification.org/page_1.asp?a=85

Geels F.W. Technological transitions of evolutionary reconfiguration processes: a multi level perspective and case study. Research Policy 31 (2002) 1257–1274

Geels F.W. The multi-level perspective on sustainability transitions: responses to seven criticisms. Environmental Innovation and societal Transitions 1 (2011) 24–40

Geels F.W., Schot J. Typology of socio-technical transition pathways. Research Policy 36 (2007) 399–417

Genus A., Coles A. Rethinking the multi-level perspective of technology transitions. Research Policy 37 (2008) 1436–1445

Gómez X., Morán A., Cuetos M.J., Sánchez M.E. The production of hydrogen by dark fermentation of municipal solid wastes and slaughterhouse waste: A two-phase process. Journal of Power Sources 157 (2006) 727–732

Guo X.M., Trably E., Latrille E., Carrère H., Steyer J-P. Hydrogen production from agricultural waste by dark fermentation: A review. International Journal of Hydrogen Energy 35 (2010) 10660–10673

Hajimiragha A.H., Cañizares C.A., Fowler M.W., Moazeni S., Elkamel A., Wong S. Sustainable convergence of electricity and transport sectors in the context of a hydrogen economy. International Journal of Hydrogen Energy 36 (2011) 6357–6375

Hawkey D.J.C. District heating in the UK: A Technological Innovation Systems analysis. Environmental Innovation and Societal Transitions 5 (2012) 19–32

Hekkert M.P., Suurs R.A.A., Negro S.O., Kuhlmann S., Smits R.E.H.H. Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change 74 (2007) 413–432

Hetland J., Mulder G. In search of a sustainable hydrogen economy: How a large-scale transition to hydrogen may affect the primary energy demand and greenhouse gas emissions. International Journal of Hydrogen Energy 32 (2007) 736–747

Hisschemöller M., Bode R., van der Kerchof M. What governs the transition to a sustainable hydrogen economy? Articulating the relationship between technologies and political institutions. Energy Policy 34 (2006) 1227–1235

Hultman M., Yaras A. The socio-technological history of hydrogen and fuel cells in Sweden 1978-2005; mapping the innovation trajectory. International Journal of Hydrogen Energy 37 (2012) 12043–12053

Jacobsson S., Bergek A. Innovation system analyses and sustainability transitions: Contributions and suggestions for research. Environmental Innovation and Societal Transitions 1 (2011) 41–57

Jacobsson S., Bergek A. Innovation systems analyses and sustainability transitions: Contributions and suggestions for research. Environmental Innovation and Societal Transitions 1 (2011) 41–57

Jinzhou W. Discussion on the relationship between green technological innovation and system innovation. Energy Procedia 5 (2011)2352–2357

Johnson A. Functions in innovation system approaches, mimeo. Department of Industrial Dynamics, Chalmers University of Technology, Sweden. 1998.

Kelrkx L., Aarts N., Leeuwis C. Adapative management in agricultural innovation systems: The interactions between innovation networks and their environment. Agricultural Systems 103 (2010) 390–400

Kim M-S., Lee D-Y., Kim D-H. Continuous hydrogen production from tofu processing waste using anaerobic mixed microflora under thermophilic conditions. International Journal of Hydrogen Energy 36 (2011) 8712–8718

Kim S-H., Shin H-S. Effects of base-pretreatment on continuous enriched culture for hydrogen production from food waste. International Journal of Hydrogen Energy 33 (2008) 5266–5274

Kobayashi T., Xu K-Q., Li Y-Y., Inamori Y. Evaluation of hydrogen and methane production from municipal solid wastes with different compositions of fat, protein, cellulosic materials and other carbohydrates. International Journal of Hydrogen Energy 37 (2012) 15711–15718

La Licata B., Sagnelli F., Boulanger A., Lanzini A., Keone P., Zitella P., Santarelli M. Bio-hydrogen production from wastes in a pilot plant reactor and its use in SOFC. International Journal of Hydrogen Energy 36 (2011) 7861–7865

Lachman D.A. A survey and review of approaches to study transitions. Energy Policy 58 (2013) 269–276

LHP 2010. London Hydrogen Action Plan 2010-2012. London Hydrogen Partnership. Greater London Authority.

Li J., Yin Y., Zhang X., Liu J., Yan R. Hydrogen rich gas production by steam gasification of palm oil wastes over supported tri-metallic catalyst. International Journal of Hydrogen Energy 34 (2009) 9108–9115

Li Y-C., Li Y-F., Chu C-Y., Chang P-L., Hsu C-W., Lin P-J., Wu S-Y. Techno-economic evaluation of biohydrogen production from waste water and agricultural waste. International Journal of Hydrogen Energy 37 (2012) 15704–15710

Li Y-C., Wu S-Y., Chu C-Y., Huang H-C. Hydrogen production from mushroom farm waste with a two-step acid hydrolysis process. International Journal of Hydrogen Energy 36 (2011) 14245–14251

London Assembly 2011. London's Wasted Resource: The Mayor's municipal waste management strategy. London Assembly publication.

Longden D., Brammer J., Bastin L., Cooper N. Distributed or centralised energy from waste policy? Implications of technology and scale at municipal level. Energy Policy 35 (2007) 2622–2634

Lui D. 2008. *Bio-hydrogen production by dark fermentation of organic wastes and residues*. PhD Thesis Technical University of Denmark.

Lundvall B.A. National Systems of Innovation. Towards a Theory of Innovation and Interactive Learning. Pinter. London 1992.

Luo G., Xie L., Zhou Q., Angeliadaki I. Enhancement of bioenergy production from organic wastes by two-stage anaerobic hydrogen and methane production process. Bioresource technology 102 (2011) 8700–8706

Markard J., Raven R., Truffer B. Sustainability Transitions: An enmerging field of research and its prospects. Research Policy 41 (2012) 955–967

Markard J., Stadelmann M., Truffer B. prospective analysis of technological innovation systems: Identifying technological and organisational development options for biogas in Switzerland. Research Policy 38 (2009) 655–667

Markard J.,Truffer B. Technological innovation systems and the multi-level perspective: Towards an integrated framework. Research Policy (2008) 596–615

McDowall W., Eames M. Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature. Energy Policy 34 (2006) 1236–1250

McDowall W., Eames M. Towards a sustainable hydrogen economy: A multi-criteria sustainability appraisal of competing hydrogen futures. International Journal of Hydrogen Energy 32 (2007) 4611–4626

Metcalfe S., Ramlogan R. Innovation systems and the competitive process in developing economies. The Quarterly Review of Economics and Finance 48 (2008) 433–446

Murray M.L., Seymour E.H., Rogut J., Zechowska S.W. Stakeholder perceptions towards the transition to a hydrogen economy in Poland. International Journal of Hydrogen Energy 33 (2008) 20–27

Musiolik J., Markard J., Hekkert M. Networks and network resources in technological innovation systems: Towards a conceptual framework for system building. Technological Forecasting and Social Change 79 (2012) 1032–1048

Negro S.O., Hekkert M.P., Smits R.E. Explaining the failure if the Dutch innovation system for biomass digestion—A functional analysis. Energy Policy 35 (2007) 925–938

Negro S.O., Suurs R.A.A., Hekkert M.P. The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system. Technological Forecasting and Social Change 75 (2008) 57–77

Ng W.P.Q., Lam H.L., Ng F. Y., Kamal M., Lim J.H.E. Waste-to-wealth: green potential from palm biomass in Malaysia. Journal of Cleaner Production 34 (2012) 57-65

Nill J., Kemp R. Evolutionary approaches for sustainable innovation policies: From niche to paradigm. Research Policy 38 (2009) 668–680

Nilsson M., Hillman K., Magnusson T. How do we govern sustainable innovations? Mapping patterns of governance for biofuels and hybrid-electric vehicle technologies. Environmental Innovation and Societal Transitions 3 (2012) 50–66

Oltra V., Saint Jean M. Sectoral systems of environmental innovatio: An application to the French automotive industry. Technological Forecasting and Social Change 76 (2009) 567–583

Roberts E.B., Fusfeld A.R. Critical Functions: Needed Roles in the Innovation Process. Working Paper. Alfred P Sloan School of Management MIT. May 1980.

Smith A., Voß JP., Grin J. Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. Research Policy 39 (2010) 435–448

Stern N. The Economics of Climate Change. Executive Summary. The Stern Review 2006.

Strachen N., Balta-Ozkan N., Joffe D., McGeever K., Hughes N. Soft linking energy systems and GIS models to investigate spatial hydrogen infrastructure in a low carbon UK energy system. International Journal of Hydrogen Energy 34 (2009) 642–657

Suurs R.A.A., Hekkert m.P., Kieboom S., Smits R.E.H.M. Understanding the formative stage of technological innovation system development: The case of natural gas as an automotive fuel. Energy Policy 38 (2010) 419–431

Suurs R.A.A., Hekkert M.P., Smits R.E.H.M. Understanding the build-up of a technological innovation system around hydrogen and fuel cells. International Journal of Hydrogen Energy 34 (2009) 9639–9654

Temel, T., Janssen W., Karimov F. Systems analysis by graph theoretical techniques: assessment of the agricultural innovation system of Azerbaijan. Agricultural Systems 77 (2003) 91–116

Truffer B., Markard J., Binz C., Jacobsson S. Energy Innovation Systems. Structure of an emerging scholarly field and its future research. A literature review. EIS Radar Paper. November 2012.

Truffer B., Markard J., Binz C., Jacobsson S. Energy Innovation Systems. Structure of an emerging scholarly field and its future research ditrections. A literature review. Chalmers University, Gothenburg. EIS November. (2012).

UK Government 2010. The National Renewable Energy Action Plan for the United Kingdom. Article 4 of the Renewable Energy Directive 2009/28/EC.

UK Government 2011. The Carbon Plan: Delivering our low carbon future. December 2011.

UK Parliament 2008. Climate Change Act 2008.

United Nations 2012. United Climate change Conference in Doha 2012. Global Concerns. Accessed online 8 May 2013 http://www.un.org/en/globalissues/climatechange/index.shtml

Vergragt P.J., Brown H.S. Sustainable mobility: from technological innovation to societal learning. Journal of Cleaner Production 15 (2007) 1104–1115

Weber K.M. Chapter 8. Foresight and adaptive planning as complementary elements in anticipatory policy-making: a conceptual and methodological approach. Reflexive Governance for Sustainable Development. Edward Elgar Publishing Limited. 2006

Welsh Government 2010. A Low Carbon Revolution. A Welsh Assembly Government Energy Policy Statement.

Welsh Government 2012. A Sustainable Wales. Better Choices for Better Future. Sustainable Development White Paper Resources Pack.

Wu D.D., Kefan X., Shi Z., Olson D.L. Modeling technological innovation risks of an entrepreneurial team using system dynamics: An agent-based perspective. Technological Forecasting and Social Change 77 (2010) 857–869

Xi-Yu C., Li Q., Liu C-Z. Coproduction of hydrogen and methane via anaerobic fermentation of cornstalk waste in continuous stirred tank reactor integrated with up-flow anaerobic sludge bed. Bioresource Technology 114 (2012) 327–333

3 Methodology

Amongst other things, Chapter 2 provided a commentary and review of the government policy and academic literature associated with technological innovation systems, particularly with respect to the sustainable production of hydrogen from waste. From this review, the research gaps that create the academic landscape for the further progression of this doctoral research were identified and justified. This Chapter now provides details of the methods selected and undertaken in order to meet the aims and objectives of this research. Each method is accompanied by a literature review.

The Chapter is structured as follows: firstly, the reasons why these methods were chosen are discussed in section 3.1, including the advantages and disadvantages of the options and an explanation of why these methods contribute to answering the main research question. The Chapter then moves on to discuss in sections 3.3, 3.5 and 3.6 the three main methods that together provide the qualitative and quantitative elements of this methodology. The three methods are described in detail along with their application. In addition, in sections 3.2 and 3.4 a literature review for the Q Methodology and Rock Engineering Systems is provided following the methodologies to which they relate. The literature reviews provide summaries of previous applications in similar fields. Finally some concluding comments are offered in section 3.7.

3.1 Methodology considerations to address research questions

This section focuses on the possible choices for participatory technology assessment techniques that could have been used to address the research gaps identified in section 2.7. Choices and decisions regarding the role of future hydrogen production are complex, uncertain and often contested. Society faces a significant challenges in relation to how and where future energy needs will be met. These challenges cover large spatial and temporal scales and decisions made may be irreversible. This leads to the desire by governments, business and academics to present a plurality of perspectives (Richards *et al.* 2007) in an attempt to ensure that decisions made do not have an adverse impact on our environment and societies. In line with the literature on reflexive governance (section 2.6), it is suggested here that perspectives should be sought to ensure a reflexive and adaptive response by governments, businesses and the public alike.

3.1.1 First sub-research question

Initially, the first sub-research question was considered:

1. *What does the comparison (Aim 2) between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?*

It was established that a conceptual model, developed to address this question, should be applied to case study regions in the UK in order to understand if the model did, indeed, reflect 'real' situations. The case study regions chosen were London, South Wales and Tees Valley. The choice of case study regions is discussed in more detail in Chapter 6.

The role of innovation systems was a key factor in deciding which model was most appropriate to address the research question above. The use of the functions of innovations conceptual framework was chosen as the reference point for an investigative model for hydrogen from waste.

The choice of the overall model to assess the case studies considered both the multi level perspective (MLP) model as described in section 2.5 and the rock engineering systems (RES) model (see sections 3.4 and 3.5). MLP was considered to be overly complex, as described in section 2.5.2, to assess the case studies in this project. RES offered an easily understood interaction matrix that could be combined effectively with the functions of innovation framework. In particular, RES provided an opportunity to examine the dynamic relationships between functions of innovation (Truffer *et al.* 2012) in a visual qualitative and quantitative manner. The RES methodology allows for the relationships that may happen in a 'real life' situation to be created in matrix form and then analysed, based on the qualitative data obtained. This means that it is possible to identify when relationships occur, and when they don't occur. Arguments can then be provided as to why this is or how the system can be improved to make the relationships occur.

3.1.2 Second research sub-question

To address the second research sub-question *How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?* participatory assessment methods were considered.

Participatory processes can help define a problem as well as contribute to the identification of a solution. Participation produces a wide variety of viewpoints, attitudes, beliefs and expectations in relation to a particular research question or project. A participation process may include stakeholders that are experts in a particular field or the wider community as a whole. The contribution from multiple stakeholders increases the understanding of the interlinked complexity and nature of problems that are multidisciplinary. This type of participatory process is useful in activities such as participatory and conflict based technology assessment (Lachman 2013). Participatory processes may be used to consider environmental issues and concerns faced by UK society today.

Participatory techniques can improve the implementation of a decision or policy where a coalition of stakeholders supports the proposal and advocates its delivery. Participation may improve relations between conflicting perspectives and speed up acceptability of a new technology or infrastructure development through learning about other views and perspectives. Cuppen (2012) describes the process of learning in participation as a frequently used technique when considering sustainable development and innovation.

To address this sub-question, a form of discourse analysis was considered a useful participatory tool. Discourse analysis is participatory and a way of understanding how different social or work identities occur, and what they can mean in terms of solving a problem or addressing a phenomenon; for example, the impact of nuclear power stations on a community (Venebles *et al.* 2009) or identifying the range of discourses around biomass (Cuppen 2009). Many aspects of our lives can influence the way we think and speak about a phenomenon; these may be cultural or political and influenced by our experiences of technologies, wealth, morality and literacy (Gee 1999). Three discourse analysis options were identified and considered, participatory and constructive technology assessment, constructive conflict methodology and Q methodology.

Potential Solution 1: Participatory Technology Assessment and Constructive Technology Assessment—The terms Participatory Technology Assessment (PTA) and Constructive Technology Assessment (CTA) are often used to mean the same activity (Tran & Daim 2008), with both terms being used equally. The processes are designed as participatory stakeholder engagement tools that help individuals, researchers, businesses and governments to make decisions on what technology can best meet their needs for future developments in energy systems, or what application is best suited to a specific technology now and in the future. This technique has been previously been applied in energy and sustainability transitions (Markard *et al.* 2012). There are two primary types of PTA/ CTA (Tran & Daim 2008):

1. Qualitative participatory technology assessment unites the scientific community with the non-scientific community. Through the development of scenarios and forecasting techniques, learning is promoted between the two different communities and ultimately moves towards a consensus. A storyline for what the participants then consider to be the most appropriate technological model is developed.

2. Quantitative participatory technology assessment—this approach uses a number of different numerical models that quantify different indicators pertinent to the development that is being explored. Then, with the input of both the expert and non-expert stakeholders, the method aims to develop a model that provides a numerical narrative confirming and countering claims made by the advocates and opponents of the proposed technological solution.

Potential Solution 2: Constructive Conflict Methodology is a method for structuring problems in stakeholder dialogue. The method is geared towards promoting learning through enhancing participants' understanding of the diversity of perspectives surrounding a particular phenomenon (Cuppen 2012). The researcher decides how the process is designed and there is no fixed approach. This method has been used to analyse dialogues relating to various subjects, including citizenship, environmental policy and other public interest topics (Tran & Daim 2008).

In reviewing these two approaches, it was judged that participatory/constructive technology assessment approaches did not present the opportunity to characterise the stakeholders involved in the innovation system, as specified by the second objective:

- *Characterise the different expert communities involved in the production of H_2 from waste in the UK and their role in the technological innovation system.*

Furthermore, constructive conflict methodology required the delivery of managed workshops to create the conflict situation between groups of participants. In this case, it was decided that in the hydrogen from waste sector there might not be sufficient stakeholders with the depth of knowledge appropriate for participation in arranged workshops.

Potential Solution 3: Q methodology is another form of discourse analysis that is used to identify and understand the different types of perceptions, beliefs and opinions of experts associated with a particular problem. This approach allows for visits to be made to the participants, along with an opportunity to audio record each Q methodology survey. A mixed method using both qualitative and quantitative analysis, Q methodology also presents a technique that reduces researcher bias and this was considered beneficial for a technological field that has a contested history, such as hydrogen. This method was considered to be appropriate for this research project, as it provides a tool that can enable the characterisation of participants, a requirement of the second objective. The Q methodology also provided the opportunity to collate the participants' varying views and beliefs of hydrogen production from waste. Q methodology is described in detail with a supporting literature review in sections 3.3 and 3.2 respectively.

3.2 Literature Review: Q methodology

In summary, the Q methodology comprises six steps, which are given in Table 3.1 below. Following this, a literature review of Q methodology applications to a variety of environmental issues is given. In section 3.3 a detailed breakdown of the Q methodology approach is provided.

Table 3.1. Summary of the six steps in Q methodology.

Step	Activity	Comments
1	Q participants	Establishing the stakeholders/ study group.
2	Developing the Concourse	Collating the communicable information surrounding the research area.
3	Selection of Q set	Extracting and selecting statements from the discourse to be used in Q survey.
4	Q sort	Carrying out the Q survey with study group.
5	Analysis of results	Analysis of Q sorts using software packages i.e. PCQ method.
6	Description and interpretation	The process of developing the group identities involved in the research group.

Q Methodology is an established form of discourse analysis that was developed by the British physicist and psychologist William Stephenson (2005). The Q Methodology aims to further advance the understanding of the scientific study of subjectivity (Brown 1980). The method has enabled social scientists to evaluate human behaviour, perspectives and expectations in many different academic subject areas.

Q Methodology was first described in Stephenson's 1953 book *The Study of Behaviour.* This celebrated work was also considered to be controversial. Criticisms included that his "claims were excessive"; he showed "misplaced contentiousness" and that he was "dwelling on irrelevancies". However, these criticisms were balanced by the judgement of psychiatrist Bernard Glueck, who welcomed Q methodology as "the long awaited stable and dependable frame of reference" for addressing the universality of uniqueness (Brown 1980).

'Discourse analysis' refers to the analysis of the way different individuals see and talk about a particular subject. This is particularly important when considering renewable technologies and other environmental studies. When considering environmental problems, some individuals, both expert and non-expert, can feel 'disempowered' by forces over which they think they have no control. In contrast to this perception, others may feel that society is more receptive to their input, while yet another group may feel that environmental issues are not an important part of their lives and that other issues such as unemployment, crime and social disillusionment are more important. These are examples of different 'discourses' and are all considered to be individual, subjective and valid. Q methodology allows for individual responses to a particular problem to be correlated and patterns between individuals identified. The recognition of these patterns can build up to the creation of 'idealised' forms of discourse pertinent to the study. These are often referred to as "factors" or "identities" (Barry & Proops 1999).

The methodology provides a foundation for the systematic study of subjectivity, which, as noted, concerns a person's viewpoint, opinions, beliefs, and attitudes on a particular subject. A Q methodology study will present individuals with a sample of statements about a particular topic; these are called the *'Q-set'*. The individual respondents, the *'P set',* are asked to rank or sort the statements from their viewpoint, according to some preference, judgement or feeling about them, mostly using a quasi-normal distribution. The use of this distribution forces the respondent to consider the statements in a systematic way (Steelman & Maguire 1999). It is presented as an inverted normal distribution grid as shown in Figure 3.2 (pg 3-40). By Q sorting, respondents give their own personal subjective meaning to the statements and, by doing so, reveal information about their personal profile or factor identity (van Excel & de Graff 2005).

Q Methodology has been studied extensively, with over 1500 works referencing the method. It is used for behavioural research across various fields, including psychology, sociology, and marketing; more recently it has moved into health studies and environmental behaviour studies (Thomas & Watson 2002).

Q Methodology may also be used to present an opportunity for citizens from different sectors of society or work places to discuss their views, perspectives, beliefs and attitudes, in a language that is familiar to them, and hence to contribute to a particular research area. Through this type of activity and discussion, individuals from different backgrounds are able to participate in a type of interactive learning where the Q methodology survey presents new ideas and perspectives not initially familiar to them. This type of discourse analysis is considered particularly useful in the fields of sustainable development, environmental management and climate change (Doody *et al*. 2009).

Pioneered by William Stephenson with specific application in the field of psychology, Q methodology has recently been popularised by Stephen Brown at Kent State University. Focus on environmental issues has been seen in several studies (Davies & Hodge 2007; Frantzi *et al.* 2009; Duenckmann 2010; Cuppen *et al*. 2010), with further applications in a multitude of academic fields.

To further understand the contribution that Q methodology can provide to the hydrogen production from waste concourse, a review of academic literature in energy and the environment was conducted.

3.2.1 Energy studies

The literature search for Q methodology studies relating to low-carbon futures and renewable energy revealed few relevant articles. This could, perhaps, mean that Q methodology's potential in this field is not fully understood. The application of Q methodology is a complex, labour intensive process (Steelman & Maguire 1999) that often takes time to produce results. Often quick results from more conventional qualitative techniques are sought instead. This may be one reason for the limited examples available in the current academic literature. There are, in fact, no Q methodology surveys relating to hydrogen production from waste biogas or syngas, and few in relation to energy or transport. By contrast, the largest proportion of Q surveys has been done in a variety of medical fields, including nursing, patient care and health studies generally, as indicated below.

A search for Q-methodology papers from 1995-2010 using the database, Science Direct, on 26/12/2010 produced the Q-methodology papers in Table 3.2. The time period for papers was chosen to reflect the greater interest in renewable technologies over the previous 15 years. The term "Q methodology" was used to search the literature.

Table 3.2. Academic Q methodology survey papers available on 07/08/2013.

Medical/Health Studies (17)
Barker, J.H. 2008. 'Q-methodology: An alternative approach to research in nurse education'. Nurse Education Today 28: 917-925.
Bryant, L.D., Green, J.M. & Hewison, J. 2006. 'Understandings of Down's syndrome: A Q methodological investigation'. Social Science & Medicine 63: 1188-1200.
Butler, M.G., Schumock, G.T., Wilken, L., Jaffe, H.A. & Mrtek, R. 'PAA15 INVESTIGATION OF THE DETERMINANTS OF ADHERENCE IN ASTHMA USING Q METHODOLOGY'. Value in Health 7: 313-314.
Chang, S.O., Kim, J.H., Kong, E.S., Kim, C.G., Ahn, S.Y. & Cho, N.O. 2008. 'Exploring ego-integrity in old adults: A Q-methodology study'. International Journal of Nursing Studies 45: 246-256.
Chinnis, A.S., Paulson, D.J. & Davis, S.M. 2001. 'Using Q methodology to assess the needs of Emergency Medicine support staff employees'. Journal of Emergency Medicine 20: 197-203.
Cross-Sudworth, F., Williams, A. & Herron-Marx, S. 'Maternity services in multi-cultural Britain: Using Q methodology to explore the views of first- and second-generation women of Pakistani origin'. Midwifery In Press, Corrected Proof.
Exel, J.v., Graaf, G.d. & Brouwer, W. 2007. 'Care for a break? An investigation of informal caregivers' attitudes toward respite care using Q-methodology'. Health Policy 83: 332-342.
Herron-Marx, S., Williams, A. & Hicks, C. 2007. 'A Q methodology study of women's experience of enduring postnatal perineal and pelvic floor morbidity'. Midwifery 23: 322-334.
Jedeloo, S., van Staa, A., Latour, J.M. & van Exel, N.J.A. 2010. 'Preferences for health care and self-management among Dutch adolescents with chronic conditions: A Q-methodological investigation'. International Journal of Nursing Studies 47: 593-603.
Morecroft, C., Cantrill, J. & Tully, M.P. 2006. 'Individual patient's preferences for hypertension management: A Q-methodological approach'. Patient Education and Counseling 61: 354-362.
Oring, K.E. &Plihal, J. 1993. 'Using Q-methodology in program evaluation: A case study of student perceptions of actual and ideal dietetics education'. Journal of the American Dietetic Association 93: 151-157.
Parker, J. & Alford, C. 2010. 'How to Use Q-Methodology in Dream Research: Assumptions, Procedures and Benefits'. Dreaming 20: 169-183.
Risdon, A., Eccleston, C., Crombez, G. & McCracken, L. 2003. 'How can we learn to live with pain? A Q-methodological analysis of the diverse understandings of acceptance of chronic pain'. Social Science & Medicine 56: 375-386.
Schamp, R.O., Chibnall, J., Peterson, D. & Van Landuyt, A. 2008. 'Lifetyles: Using Q-Methodology to Assess Quality of Life and Care Priorities in Frail Elders'. Journal of the American Medical Directors Association 9: B16-B17.
Stenner, P.H.D., Cooper, D. & Skevington, S.M. 2003. 'Putting the Q into quality of life; the identification of subjective constructions of health-related quality of life using Q methodology'. Social Science & Medicine 57: 2161-2172.

Stenner, P.H.D., Dancey, C.P. & Watts, S. 2000. 'The understanding of their illness amongst people with irritable bowel syndrome: a Q methodological study'. Social Science & Medicine 51: 439-452.
Yeun, E. 2005. 'Attitudes of elderly Korean patients toward death and dying: an application of Q-methodology'. International Journal of Nursing Studies 42: 871-880.
Miscellaneous (6)
Bracken, S.S. & Fischel, J.E. 2006. 'Assessment of preschool classroom practices: Application of Q-sort methodology'. Early Childhood Research Quarterly 21: 417-430.
Militello, M. & Benham, M.K.P. 2010. '"Sorting Out" collective leadership: How Q-methodology can be used to evaluate leadership development'. The Leadership Quarterly 21: 620-632.
Robbins, P. & Kimberly, K.-L. 2005. 'Q Methodology' Encyclopedia of Social Measurement. New York: Elsevier.
Stephenson, W. 1980. 'Newton's Fifth Rule and Q methodology: Application to educational psychology'. American Psychologist 35: 882-889.
ten Klooster, P.M., Visser, M. & de Jong, M.D.T. 2008. 'Comparing two image research instruments: The Q-sort method versus the Likert attitude questionnaire'. Food Quality and Preference 19: 511-518.
Wittenborn, J.R. 1961. 'Contributions and current status of Q methodology'. Psychological Bulletin 58: 132-142.
Van Excel N.J.A., de Graaf G., & Rietveld P. Getting from A to B: Operant approaches to travel decision making. Journal of the International Society for the Scientific Study of Subjectivity (27) 4 (2004)
Environment/ Climate Change and Energy (6)
Barry, J. & Proops, J. 1999. 'Seeking sustainability discourses with Q methodology'. Ecological Economics 28: 337-345.
Cuppen, E., Breukers, S., Hisschemöller, M. & Bergsma, E. 2010. 'Q methodology to select participants for a stakeholder dialogue on energy options from biomass in the Netherlands'. Ecological Economics 69: 579-591.
Curry R., Barry J., & McClenaghan A. Northern Visions? Applying Q methodology to understand stakeholder views on the environmental and resource dimensions of sustainability. Journal of Environmental Planning and Management. 2012 10.1080/09640568.2012.693453
Davies, B.B. & Hodge, I.D. 2007. 'Exploring environmental perspectives in lowland agriculture: A Q methodology study in East Anglia, UK'. Ecological Economics 61: 323-333.
Doody D.G., Kearney P., Barry J., Moles, R., & O'Reagan B. Evaluation of the Q-method as a method of public participation in the selection of sustainable development indicators. Ecological Indicators 9 (2009) 1129–1137
Duenckmann, F. 2010. 'The village in the mind: Applying Q-methodology to re-constructing constructions of rurality'. Journal of Rural Studies 26: 284-295.
Eefje Cuppen: A quasi-experimental evaluation of learning in a stakeholder dialogue on bio-energy. Research Policy (40) 2012
Frantzi, S., Carter, N.T. & Lovett, J.C. 2009. 'Exploring discourses on international environmental regime effectiveness with Q methodology: A case study of the Mediterranean Action Plan'. Journal of Environmental Management 90: 177-186.
Niemeyer S., Petts J., & Hobson K. Rapid climate change and society: Assessing Responses and Thresholds. Risk Analysis (25) 6 (2005)
Rajé, F. 2007. 'Using Q methodology to develop more perceptive insights on transport and social inclusion'. Transport Policy 14: 467-477.
Venables D., Pidgeon N., Simmons P., Henwood K., & Parkhill K. Living with Nuclear Power: A Q-Method Study of Local Community Perceptions. Risk Analysis Vol. 29, No. 8, (2009) 1089–1103

Table 3.2 shows clear preferential use of the methodology within the medical and health studies field, with seventeen papers produced using only a very basic search. The table also shows that it is only from 2007 that Q methodology has been used to

analyse the subjectivity of participants about the environment, climate change and energy sector. The exception to this is the paper by Barry & Proops (1999) that demonstrates clear foresight of the advantages of Q methodology to develop social perspectives around sustainability.

The articles identified with particular relevance to renewable energy technologies and environmental concerns will be reviewed. The emphasis of this review will be on the energy, transport, sustainable development, and climate change papers. A summary of the papers is presented, covering the methods used and reporting on the author's experiences and conclusions of Q methodology. The review will aim to bring to light the important aspects of the methodology that will advance understanding, satisfy curiosity or further illuminate problems surrounding the use of Q methodology in the field of technological innovation systems for the production of hydrogen from waste. Split into different sectors, the review reports on the moderately differing uses of conventional Q methodology (Duenckmann 2010).

3.2.2 Environment, Agriculture and Rurality

The first section reviews three papers that relate to rurality, environmental regimes and agriculture, published from 2007-2010. These are considered first because they all undertake a Q methodology study to further enhance understanding of a particular group of individuals within their sector.

Presented chronologically, the first paper in this section is by Davies & Hodge (2007), *Exploring environmental perspectives in lowland agriculture: A Q-methodology study in East Anglia, UK*. This study aimed to uncover the environmental views and perceptions of a group of arable farmers in the East Anglian region of the United Kingdom.

Davies & Hodge (2007) based their Q-methodology survey on a much larger number of participants than is usually found in Q studies, over one hundred. Normally, there would be in the region of twenty-five to thirty participants (Frantzi *et al.* 2009; Duenckmann 2010) although the number of Q statements in the Q sort can also influence the number of participants. The number of statements used in this study was thirty-three, making the number of participants even more unusual, as more often than not the number of statements in a Q sort is expected to outnumber the participants. Another noteworthy aspect of this study is that Davies and Hodge (2007) choose to develop the statements without any verbal input from the participants. They describe these statements as being “written specifically” for this study. This can be interpreted as meaning that they did not use existing statements directly from the literature. Instead, they interpreted the concourse (the concourse is all the discourses surrounding a phenomenon) themselves and chose to write statements that suited their requirements for the sub-categories, relating to conservation and environmental management. These statements were then pre-tested on six volunteer farmers. The use of “specifically written” statements is unusual, because one of the key strengths described in Q literature is the advantage provided by Q methodology that:

“…it limits the research bias because the statements are generated purely by the participants and not imposed by the researcher…” (Frantzi *et al*. 2009).

However, in this case Davies & Hodge (2007) have broken with this convention.

The Q-sort was carried out using a nine-point scale with zero salience at the central point of the matrix. The study then performed a varimax rotation using the PQMethod software, producing five types based on the number of individuals weighting on specific factors. These five types of arable farmers are described using a narrative to show their relationships and differences to each other.

Davies and Hodge (2007) conclude that Q methodology itself has provided a useful investigative approach with a level of sophistication beyond conventional standard structured surveys (R-method). The sophistication described relates to the comparison of perspectives and attitudes between the different types of farmers that goes beyond simply sorting them into groups based on similar responses. Furthermore, it is reported that the approach was received positively by the participants, leading to a good level of engagement in the Q-sorting process.

The second paper in this section explores the effectiveness of environmental regimes by studying the Mediterranean Action Plan (Frantzi *et al.* 2009). The subject of this paper is whether different stakeholders involved in the implementation of an international regime share a common understanding of "effectiveness", or whether there are different interpretations of this concept. The measurement of this type of subjectivity differs from the Davies & Hodge (2007) study as it considers "understanding of a concept" rather than "what's your attitude towards?" Q methodology is no less effective in producing social discourses for these types of subjectivity, but it is important to recognise the different types of perceptions and attitudes that are studied.

As suggested earlier when outlining the methodology, more generally the choice of participants can be done either at the very beginning of the process or after the development of the concourse. In this case the stakeholders were identified at the beginning of the project. The researchers then developed the Q statements using both literature and semi-structured interviews with the selected participants. This produced verbal statements that could be reproduced alongside the statements drawn from the literature to produce the forty-four statements finally used with twenty-five participants.

The Q-sort was then carried out using a nine-point scale reflecting agreement or disagreement with statements. From the studies reviewed in this section, the nine-point scale appears to be preferred to the eleven-point scale (Davies & Hodge 2007; Frantzi *et al.* 2009; Duenckmann 2010). The participants were not forced to use a quasi-normal distribution as Frantzi (2009) was concerned that this could confuse them, and felt that the distribution effects of allowing a more natural distribution are virtually non-existent. PQMethod software was used to carry out the statistical analysis, producing four social discourses on international regimes. The participants were chosen based on their backgrounds and occupations, and were considered to represent the discourses involved in the development of the action plan. This suggests that the statements used produced the expected outcomes from different stakeholders, thus confirming the capacity of Q methodology to reveal patterns of shared beliefs and attitudes across individuals. This outcome reinforces the argument that Q methodology is a suitable method for the study of contentious and widely debated social phenomena (Barry & Proops 1999), such as the environment, climate change and sustainable development, together with the technologies and activities associated with these fields.

Frantzi (2009) summarises the advantages of Q methodology: requiring only a small number of participants in order to generate statistically significant results; and its reduced bias due to its participant driven nature. However, it also notes limitations that should be accounted for. The statistical procedure may be easy to perform, but, as noted earlier, the initial stages of a Q methodology research project are very intensive and time consuming for the researcher (Frantzi *et al*. 2009). The conclusion from this study shows that Q methodology is suitable for research activities akin to doctorates as the depth and intensity to which it is carried out fits well into research over a period of years. However, Q methodology is beginning to reveal itself as less appropriate for some areas of mainstream research that require low time commitment and limited literature review from the researcher. More conventional qualitative methods, such as surveys and interviews, have the advantage here because they can produce fast results with less front end input.

Finally, Duenkmann (2010) seeks to understand views and perceptions of the understanding of rurality. He describes notions of ‘the rural’, and how they are constructed by individuals with an equally relevant and valid viewpoint into everyday life. This study aims to ascertain if affiliation to a certain group fully determines an individual’s subjectivity or if other factors influence perceptions of the world. This study is similar to (Frantzi *et al.* 2009) as it is considering “understanding a concept”, in this case ‘rurality’.

Duenkmann (2010) clarifies that the Q methodology is based on the ranking of stimuli, usually controversial in nature, by chosen test persons. The statistical analysis of these Q-sorts resembles ‘normal’ factor analysis, but with one fundamental difference: while normal factor analysis correlates tests over a number of individuals, Q methodology correlates persons over a number of tests. The factors resulting from this process can be described as re-constructions of commonly shared views on which the individual respondents load with a higher or lower degree. This differs from more conventional methodologies that analyse how an individual's responses to survey questions are distributed across the population, whereas Q methodology seeks to understand the internal constructions of opinions and activities with reference to a specific subject. It is not possible to "scale up" the responses from Q methodology to represent an entire population; they can only be seen as the responses and commonly formed identities of the study group undertaking the Q methodology survey. This may limit some studies that seek to understand large populations. However, the method may work well for case study regions, small study populations or to understand particular phenomena.

This study by Duenkmann (2010) developed the concourse using exploratory interviews with participants to produce statements in a language that could be understood by all participants. Forty-three statements were used in the Q-sorts with thirty participants who were active in the concourse development. As with the previous two papers, this study used a nine-point scale. However, this study differs from those of Davies & Hodge (2007) and Frantzi *et al.* (2009) as the Q-sorts were carried out at the same time as a more qualitative interview approach, with participants being encouraged to describe their choices for the Q-sort. This type of Q-sort can provide clarity in the production of the social discourses because the anecdotal and descriptive nature of this type of sorting adds depth to the qualitative data collected. This study also chose to use the PQMethod software that is freely available online to carry out a varimax rotation. The statistical analysis produced three factors and the statements of these factors were analysed and used to reconstruct the characteristics found in each factor.

Duenkmann (2010) concludes that Q methodology aims at the plurality of perspectives on a certain topic. It is, he suggests, an appropriate method to explore the different concepts of rurality that co-exist within a village or municipality. An important advantage is that Q methodology can take the constructions of reality themselves as the central objects for analysis, and not the individuals that hold them. Thus it is possible to bypass the risk of readily falling back on the distinctions between pre-existing groups or socio-demographic factors and ascribing certain positions to them.

All three of the papers reviewed in this section have considered Q methodology a positive approach that produced the types of results that they had hoped to achieve. The authors used the results of these studies to reconstruct statements from Q methodology into social discourses. However, despite its advantages described in this section, the following must be remembered:

"…Q methodology does not free the researcher from his or her responsibility to make assumptions, to take decisions and to interpret results. But this should not be seen as a burden, but rather as an invitation and a challenge to accept the task of re-constructing other peoples' construction of the world we co-inhabit…" (Frantzi *et al*. 2009)

3.2.3 Climate Change and Sustainable Development

This section will focus on the Q methodology papers in the fields of climate change and sustainable development. There are three papers exploring the fields of rapid climate change and society, sustainability discourses, and selections of sustainable development indicators. These papers were published over a longer time span than the previous three papers reviewed, i.e. 10 years; they are firstly Barry & Proops (1999), then Nieymeyer *et al.* (2005) and finally Doody *et al.* (2009).

The paper, "Seeking sustainability discourses with Q methodology"(Barry & Proops 1999), was published in *Ecological Indicators*; it is one of the most cited Q methodology papers, with seventy-two citations. It is cited in all environmental, climate change, energy and transport Q methodology papers found for this doctoral research review. It is likely that this paper is so highly cited because it provides a very clear description of the methodology. The paper also provides a case study example, making the application of Q methodology easily transferable to a researcher's own project.

In 1999 when this study was published, Q methodology was a relatively little-known form of research methodology within social science, even though at this stage it had been established for over 60 years (Barry & Proops 1999). For this publication, only eight citations are used throughout the paper compared with 60 from more recent Q studies (Duenckmann 2010).

The application of Q methodology within this study falls into what is becoming the ‘standard’ form and it is likely that this is because many other studies have been formulated from this paper. Barry & Proops (1999) aimed to understand the attitudes of members of Local Employment and Trading Systems in the UK. The Q study focussed on three distinct areas of citizen and community, environmental concern, and awareness and sustainability. This particular paper reports on the environmental concern aspect of the Q study.

The study used semi-structured face-to-face interviews with academic and popular literature used to produce the statements used for the Q-sorts. A large number of statements were initially produced and a sixteen cell (4 x 4) matrix was used to sort the statements into themes. After this, the most valuable statements were identified and the number of statements reduced to thirty-six.

This method of thematic categorisation assists in reducing statements down to a manageable number while reducing (but not eliminating) researcher bias as the researcher still has to choose the themes and the statements that fit into them. (Dryzek & Berejikian 1993). The researcher may choose to select an even number of statements from each category (Barry & Proops 1999).

PCQsoft and PQMethod are both statistical software programs designed to analyse the results of Q-sorts.
PCQsoft is a paid for software with an interface that resembles the grids used in Q-sorts. The software is easily uploaded to a PC and may be used immediately.
PQMethod is free software originally developed using Fortran coding in 1992. PQMethod's main limitation is that it is must be downloaded and configured on the researcher's computer.
Other software exists for Q methodology analysis including FlashQ, QAssesor and WebQ.

Details of all software is available at http://qmethod.org/links

Box 3.1. Details of software available for Q methodology analysis.

Thirty participants were required to sort the thirty-six statements using the nine-point scale; this is also the case with the previous papers in this Q methodology review. Again, the continued use of the nine-point scale suggests that it is the most appropriate for Q methodology because it adds the least confusion for the participant carrying out the Q-sort. In this instance, PCQ software (PCQ Method Website 2012) was used to carry out the statistical analysis and varimax rotation. PCQ (PCQ Method Website 2012) software provides a complete package to analyse Q methodology surveys. The software operates in both Windows and DOS, with a user interface that is visually similar to the grids used in Q sorts. It is unclear why they have chosen this software as there are a number of free downloadable packages that perform the varimax rotation and produce factor analysis; the most popular now being PQMethod (Niemeyer *et al.* 2005; Davies & Hodge 2007; Frantzi *et al.* 2009; Duenkmann 2010;). Details of the software available for Q methodology analysis are given in Text Box 1. PQMethods is the original Fortran program developed in 1992 at Kent State University.[1]

[1] PQMethod is a statistical program tailored to the requirements of Q studies. Specifically, it allows the easy entry of data (Q-Sorts) in the way they are collected, i.e. as 'piles' of statement numbers. It computes inter-correlations among Q-Sorts, which are then factor-analysed with the Centroid or, alternatively, PCA method. Resulting factors can be rotated either analytically (Varimax), or judgmentally with the help of two-dimensional plots. Finally, after selecting the relevant factors and 'flagging' the entries that define the factors, the analysis step produces an extensive report with a variety of tables on factor loadings, statement factor scores, discriminating statements for each of the factors as well as consensus statements across factors, etc. The original FORTRAN program, QMethod, was developed by John Atkinson at Kent State University in 1992 for mainframe platforms, and released to the Public Domain. It was ported by the maintainer of this site to the PC and updated with added features to versions 2.xx later on. http://www.lrz.de/~schmolck/qmethod/index.htm

The PCQ and factor analysis produced four discourses on the environment that are re-constructed for this part of the larger study.

Barry & Proops (1999) conclude that it is on the basis of such environmental discourses that we might hope to construct socially acceptable and effective environmental policies. Furthermore, "…if it is possible to identify that certain groups have discourses about nature that are markedly different from other groups then policy makers will know that policies acceptable in one locality or stratum of society, may be ineffective or even unworkable elsewhere…".

The second paper (Niemeyer *et al.* 2005) in this section uses mixed methods of scenario development and Q methodology to understand potential social responses to climate change. These responses to climate change were elicited using four climate change scenarios. This study had twenty-nine participants from a range of socio-economic backgrounds, who had an interest in the subject. Statements were drawn from a series of interviews. Each participant undertook four Q-sorts, where the participant carried out the sort based on how they felt during that scenario. The Q-sorts were carried out face-to-face and the interviewer provided scenario background and assistance to each participant. The sort was carried out using a nine-point scale with a total of 116 Q-sorts being produced. One significant difference in this study when compared to others is that here a forced distribution is used. This means that quotas of statements were assigned to each response category and participants had to sort in accordance to these quotas. There are two primary arguments regarding the use of a forced distribution. The first given in this study is that forced distribution encourages the participant to think harder about the statements and how closely they fit to their way of thinking (Niemeyer *et al.* 2005). The opposing argument is that, statistically, the forcing of the distribution has a negligible effect on the quality of the data and simply confuses the participant carrying out the sort (Barry & Proops 1999; Niemeyer *et al.* 2005; Davies & Hodge 2007; Frantzi *et al*. 2009; Duenckmann 2010). Niemeyer *et al.* (2005) also state that due to the onerous nature of completing four Q-sorts the quotas were never strictly enforced. Where a researcher requires participants to carefully analyse how important or relevant a statement is, then forced distribution has its place. In other situations, where researchers may require a freer thought process, the unforced process may be seen as more appropriate. For the case of hydrogen from waste the forced distribution is more appropriate. It is important that each participant carefully analyses how each statement fits with their way of thinking.

Niemeyer *et al.* (2005) conclude by stating that the method used to obtain the results involved the extraction of four subjective factors representing major discourses that potentially influence behavioural responses to climate change. Furthermore, the need for refinements notwithstanding, the use of Q methodology in combination with climate change scenarios has proved a promising approach. It has enabled the systematic investigation into a range of social responses to climate change, and the existence of potential thresholds between adaptive, non-adaptive and maladaptive behaviour .

Most recently Doody *et al.* (2009) published "Evaluation of the Q-method as a method of public participation in the selection of sustainable development indicators". In this study Q methodology has been employed to produce social discourse identifying views, attitudes and beliefs around sustainable development. Additionally, the indicators produced from that discourse can be used within government policies and strategy to represent a more universal understanding of sustainable development (Doody *et al.* 2009). Doody *et al*. (2009) aimed to utilise the flexibility of Q methodology as a bottom-up approach to identify and prioritise public opinion on sustainable development. The results of the Q study were then analysed by experts to produce sustainable development indicators.

In Doody *et al*. (2009) the concourse was developed using eleven focus groups developed from a stakeholder analysis. These focus groups each contained between eight and eleven individuals from core stakeholder groups concerned with sustainable development indicators. The focus groups produced over 700 statements and a sixteen cell (4 x 4) matrix was used to reduce the statements to a manageable size. There were fifty statements and thirty-seven participants undertook the Q-sort, which featured a nine-point scale. In this instance PCQ software was used to carry out the statistical and factor analysis and to carry out the varimax rotation determining the final set of factors. Finally, an ideal Q-sort was identified for each factor producing a 'representative' participant correlated factor (Doody *et al.* 2009). The 'ideal' sort was developed from the statements with frequently high or low weightings occurring across all participants in each factor.

Six ideal Q-sorts were produced and from these social discourses as well as sustainable development indicators were obtained. Only two to three indicators were produced from each factor in this study; using further participation techniques further sustainable development indicators were developed. The six discourses identified during the process were claimed to provide policy makers with a representative reflection of public opinion about sustainable development (Doody *et al.* 2009).

Doody *et al*. (2009) conclude that the Q method helped the participants to make a significant and worthwhile contribution to the development of indicators by allowing them to discuss sustainable development in their own words and in the context of their lives. As a result, it is said, the participants in this study were generally happy with their participation and felt that they had learnt about sustainable development during the process.

3.2.4 Transport and Energy

The final section of this review concentrates on the Q methodology papers most closely aligned to technological innovation systems for hydrogen production from waste. This section comprises four papers, two transport studies and two energy studies.

The transport based Q methodology studies by van Excel *et al*. (2004) and Raje (2007) consider travel behaviours and the impact of transport on members of different social groups respectively. Although the subject areas are related, the studies themselves are quite different.

Van Excel (2004) provides the only example of a mail based Q methodology study carried out by participants with no assistance from the researchers. However, they overcome some of the difficulties of interpretation of the Q-sorts by conducting a qualitative follow up interview with each participant. This study was carried out as part of ongoing research with the concourse created from previously unpublished work and the addition of post Q methodology surveys, creating a unique research method.

In contrast to van Excel (2004), Raje (2007) approaches the Q methodology more conventionally. Here the concourse is created purely from existing academic and grey literatures without any verbal contribution from participants. This produces Q statements in the language of the researcher rather than that of the participants and increases bias. This is due to the researcher deciding what statements are relevant to the research field.

Raje (2007) also suffered from confounding factors due to participants weighting too heavily on single factors or groups of statements. (This occurs when too many participants weight too heavily on too many statements in the Q survey meaning that a factor variance is too great, preventing a clear identity being revealed for that Q-sort. It is possible that this could have been caused by the way the concourse and statements were created.

The final two papers are energy based studies. One considers the risk of nuclear power on local communities (Venebles *et al.* 2009) and the other considers stakeholder selection for biomass dialogue in the Netherlands (Cuppen *et al.* 2010). These papers could have facilitated the construction of factors for group perspectives on nuclear power and biomass energy respectively. The results of these studies have not been used in this manner. The studies have, however, been used to identify risks associated with living in communities near nuclear power stations and to choose stakeholders for further participatory activities. It is possible that in both of these studies the social discourses produced around energy were used to further inform research into low-carbon technologies and behaviours, but it is not evident in the papers.

The study by Venables *et al*. (2009) relating to nuclear power uses a generic Q methodology in most senses, but has a participant group that is larger than the number of Q statements, and this is unusual. In this case, the researchers are examining two case study areas of Bradwell-on-Sea and Oldbury-on-Severn, the location of two nuclear power stations. Equal numbers of participants undertook the Q methodology in each region. A conventional ratio of statements where the number of statements is greater than participants was changed from 62:42 to 62:84, with the number of participants greater than the statements. There is not enough evidence to understand if this alteration in the ratio has any impact on the statistical results and subsequently the construction of social discourses in the research field. It is clear in the Q methodology primers that the number of statements should exceed the participants, as described in section 3.3.

> This ratio is important as it aims to ensure that distinctly different groups are revealed in the course of carrying out a Q methodology. It may be possible if the participant to statement ratio is too close that too many different groups are identified. It could be suggested that this would not be a useful result.
>
> "…It is important to have fewer Q participants than Q statements. Normally a ratio of 3:1 is used. For a study of 45 Q statements, the ideal number of Q participants would be 15. The highest ratio that should be used is 2:1. Many studies involve between 12-20 participants…"(Webler *et al*. 2009 pg 2)

From the statistical analysis using PQMethod, four prototypical sorts emerged that were then reconstructed into social discourses or factor identity groups.

In the (Cuppen *et al*. 2010) study relating to biomass the production of social discourses through the application of Q methodology is used to produce groups of stakeholders in the same way that (Doody *et al*. 2009) produced groups of sustainable development indicators. Members of the research team reduced the large number of statements to seventy and the Q sort was undertaken by seventy-five participants; again a larger number than that of the statements. The Q sorts were analysed using PQMethod and six different perspectives on biomass were produced. The perspectives produced were used to identify stakeholders for subsequent dialogue. Using the weightings of participants on particular factors, the research team identified archetypal sorts for each factor and participants that closely shared that perspective, thus reducing participants from seventy-five to thirty for the subsequent Biomass Dialogue (Cuppen *et al.* 2010).

3.2.5 Literature Review Concluding Comments

There is a clear base Q methodology emerging from this literature review and the use of this methodology has increased particularly in recent years, with most Q studies happening in the eight years from 2005 onward (Table 3.2). This increase in application may be due to one of the primary advantages of Q methodology, which is the reduction of bias due to the concourse being created by participants, in addition to the use of academic and grey literatures (Frantzi *et al.* 2009). The concour*se is c*onstructed by the researcher initially through interviews and analysis of literature. It is then deconstructed into statements used in the Q survey and finally factor identities are reconstructed following the analysis of the Q sorts.

Primers provide an outline structure that Q methodology studies should follow. However, from the studies reviewed it can be seen that researchers can adapt the way they create the discourse, the number of participants involved and the choice of analysis they carry out. Studies that utilise best practice methods can be adapted to fit research seeking to understand a particular group of stakeholders' views, perspectives and beliefs on a specific topic. From the studies in this review a base Q methodology for this research has been derived and is described in detail in section 3.3.

This review shows the flexibility of Q methodology, particularly when applied to improving understanding of contested and controversial issues; it can be combined with conventional qualitative methods, known as R methods, or traditional survey techniques to broaden the population being examined. It can also be used with other participatory techniques, such as scenario development, that allow for a more critical view of subjectiveness for a particular topic. This could include future environmental and energy concerns or other desired changes in society.

Q Methodology offers important opportunities to the participants, particularly the act of learning within a participatory situation. Q methodology offers the participant the opportunity to discuss his or her own understanding of a subject and consider statements generated by other participants that may or may not fit with their world view. The process of reflection during the Q-sort process may help participants to contemplate how their view fits into a potentially larger picture, and how they may form relationships with other participants. In the case of technological innovation in hydrogen production from waste this may be especially important due to the combination of different stakeholders involved in this emerging area who may have limited awareness of each other. They may not know if they can assist or hinder each other in the development of a low-carbon future. While Q methodology only provides a tool to assist in understanding the relationships between the stakeholders who participate in the Q methodology survey, it may be helpful.

3.3 Q Methodology: Base methodology and application

Q methodology is usually practised in the six stages given in Table 3.1; this section will outline those stages. This base methodology has been used in this research. It is not always carried out in this way and in some instances two stages of Q methodology may be incorporated into one stage.

Stage 1. Stakeholder analysis (Q-participants or the P-set) – The stakeholders or study groups are the individual participants who will undertake the Q methodology survey. The P-set should represent the divergence of opinion in a target population and not the distribution of beliefs across the whole population. They are individuals who have an interest or a stake in the field of study. The type of stakeholder analysis carried out is wholly dependent on the research area and whether the research aims to observe and analyse the perceptions, opinions and beliefs of a group of experts, or the general public or a mixture of both. It is often the case that a stakeholder analysis is carried out in order to specify an inclusive environment that provides an open and transparent approach to the decision and policy making process within government and business. Stakeholder analysis techniques may be used in order to identify key individuals who have an interest in particular research activities. Ensuring the participation of these individuals in the Q methodology process may enrich potential outcomes by ensuring that consideration is given to all expert groups involved. For example, for hydrogen production from waste, it may be necessary to include stakeholders from waste management, waste and energy policy, hydrogen production research and regulators for these sectors. Each stakeholder involved is considered to have a stake in the phenomenon under investigation. However, an important choice to be made in stakeholder analysis lies in deciding whether the phenomenon under investigation should dictate which stakeholders are involved, or whether the stakeholders create the phenomenon (Reed *et al*. 2009).

Analytical categorisation is an option for identifying stakeholders for the production of hydrogen from waste and includes: analysis using levels of interest and influence, co-operation and compensation, co-operation and threat and urgency, legitimacy and influence. One popular method, for example, is using influence and interest to classify stakeholders into 'key players', 'context setters', 'subjects' and 'crowd'. This type of analysis can help to identify how stakeholders may be engaged depending on their interest or influence over the particular research field (Reed *et al*. 2009).

Different stakeholders are usually entered into a matrix similar to Figure 3.1, enabling researchers, governments or businesses to visualise the role of different stakeholders in their activities. More complex matrices can be developed where more variables are considered and the choice of position is not based solely on the subjectivity of the analyser, but considers their activities or influence on others and technologies in a sector.

In order for the stakeholder analysis to be an effective tool in Q methodology, at least some of the stakeholders identified must be open-minded visionaries, because they are able to bring a viewpoint that may not be influenced by the area of study. More practical, strategic and regulatory stakeholders must also be found to temper these visionary stakeholders. Finding this diversity of individuals to participate provides the first challenge of Q methodology (Kerckhof & Weiczorek 2005). The literature suggests that the process of identifying and reorganising stakeholders into categories, and requesting they suggest the recruitment of appropriate individuals from different sectors, may be useful. These would be individuals who they feel may have an interest or enrich the diversity of stakeholders. This could be based on an individual's working relationship with others or knowledge of their work activities through other networks. Consequently, an initial stakeholder's position in the field may become less significant or more significant as additional stakeholders emerge. This activity, known as the snowball method, must be included if a stakeholder analysis is to be effective.

The matrix identified is one variation of a number of matrices and frameworks that have been developed, based on a general theme first identified by (Freeman 1984). Freeman established a variety of interest/influence and relationship matrices and visual models to show how different stakeholders affected businesses. From that basis many different models have been developed and used. These models ask of stakeholders, what is their interest and what is their influence? This is followed by how can they be influenced and what is their commitment to the project?

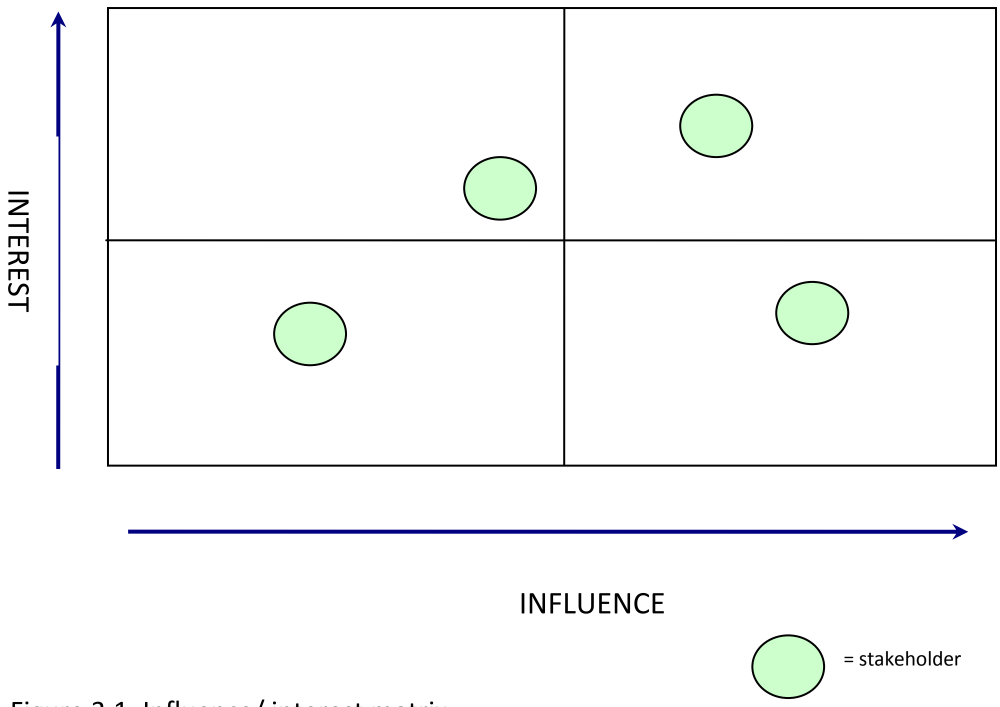


Figure 3.1. Influence/ interest matrix

The stakeholder analysis produces a list of people who will be requested to undertake the Q-sort survey. They are called the Q-participants or 'P-set', as noted earlier. These participants, through the application of the stakeholder analysis, will be representative of a population with a relationship to the research or subject area. Individuals with well-informed opinions will find it easier to do the Q-sort and are more likely to produce robust results and may define subsequent factor identities (Webler *et al.* 2009).

The development of the P-set is often carried out after the production of the concourse and Q-set (both described below), however it is often necessary to know which participants are able to contribute a depth of knowledge, opinion, perspective, belief and counter claims prior to interviews, thus ensuring clarity, accuracy, breadth of ideas and claims across the concourse. This is managed by categorising the stakeholders and ensuring that they remain engaged with the process. A number of individuals chosen to participate in the P-set may sometimes have been instrumental in developing the concourse; this could be due to their depth of knowledge and experience in the field. In an emerging subject like hydrogen production from waste, this may be the case.

Stage 2. Developing the concourse – 'Concourse' is a term used to describe the flow of communicable information surrounding the area being researched. This term should not be confused with the concept of discourse. The concourse is used to produce the Q statements which will be used in the Q-sort (Van Excel 2005). The concourse can be developed by using a number of different methods; carrying out a literature review can produce a significant number of academically sourced facts and opinions, while expert semi-structured surveys or interviews (e.g. interviews with open ended questions) can also produce significant statements including verbal anecdotes, personal opinions and beliefs. The use of semi-structured surveys or interviews is often an efficient and practical way of creating the concourse, because it can ensure that all relevant aspects of the subject are explicitly discussed with nothing being systematically eliminated (Webler *et al*. 2009).

Other sources of information for the concourse can be obtained from media, newspapers, magazines, even novels and essays. The concourse does not have to be factually accurate, as Q methodology seeks to analyse different perspectives, attitudes and beliefs and these are not always based on facts. The depth of the material collected for the concourse will dictate the sophistication of the concourse itself (van Excel 2005) and subsequently the whole Q survey.

Stage 3. Selection of Q-set – this is a selection of statements taken from the concourse that participants are asked to respond to (Barry & Proops 1999). This Q-set often consists of forty to fifty statements, but less or more may be used (van Excel 2005). The development of the Q-set is not a science; it falls to the investigator to decide which statements from the concourse are suitable for the Q-set. This means that different researchers in the same field may choose different Q-statements from the same concourse.

Good Q-statements should be short, stand-alone sentences that are easy to read and understand. An important quality of Q-statements is that they contain 'excess meaning'. This means that the participant should have the opportunity to interpret a Q-statement. Each participant may interpret the statement in a different way and this contributes to the reconstruction of factor characteristics. Most importantly the Q-statements must accurately represent the opinions in the concourse (Webler *et al*. 2009).

Once a large number of statements have been developed they can be strategically sampled by sorting the statements from the concourse into themes. These themes can be pre-existing from subject literature within the concourse or emerging through the process of developing the concourse from interviews, anecdotes or grey literature. Finally, from a large selection of Q-statements covering, for example, six themes, the five best or most applicable statements from each theme are chosen, producing a Q-set of thirty statements. This is the Q-set that is used for the Q-sort (Webler *et al.* 2009).

The P-set is usually smaller than the Q-set, with an aim to have four or five individuals defining each anticipated viewpoint (Van excel 2005).

Stage 4. Q-sort – This is the process of ranking the Q-set. Q-statements are written on individual cards and are randomly numbered. The respondent is asked to rank the cards according to some rule or scale; this is usually based on 'most disagree' to 'most agree' (van Excel 2005) with between 9 and 11 points (-5 to +5) with '0' as neutral. Using '0' as neutral forces a normal distribution. Sometimes researchers using Q-surveys allow the participants to choose at what point on the scale their neutral point is. Webler et al. argue that 'knowing the zero point is of interest'. They ask their participants at the end of the Q-sort to point out which point demarcates agree from disagree on the 9 or 11 point scale. The point at which each participant identifies a point where they begin to disagree with the statements is very useful in the writing up of social perspectives (Webler *et al*. 2009). However, allowing the respondent to choose the neutral point also adds greater complexity to the results and subsequently the analysis.

Cards are placed onto the matrix grid as shown in Figure 3.2 (show below on page 3-41). The example given is for a Q survey using 55 statements. The kurtosis of the distribution depends on the controversiality of the topic and diversity of participants. Allowances should be made for varying levels of knowledge on the subject, indecisiveness of respondents, strong or well-articulated arguments and salience. Taking all factors into account will affect the flatness or steepness of the distribution (van Excel 2005).

Stage 5. Analysis of results – Q methodology uses factor analysis, which is a mathematical technique used to reveal underlying explanations for patterns and trends produced from the collated data. Factor analysis is carried out using one of a number of software packages. These packages include the PQMethod software[2] as well as online tools such as, QAssessor and FlashQ[3]. PQMethod is used to analyse Q-sorts that have been conducted by hand on a paper grid. QAssessor and FlashQ are computer based interfaces that conduct the Q sorts and analyses online. The software will produce a number of 'factors' which are particular arrangements of the Q statements. These factors are idealised Q sorts since they are produced using analysis and social perspectives based on the Q sorts or subjective expressions of the participants (Webler *et al.* 2009). These are often termed identities.

Stage 6. Description and interpretation – This is the process of developing the factor identities further. Perspectives revealed may clash directly with each other, they may be complementary or they may differ in non-confrontational ways. The comparative analysis and narration of these social perspectives should account for these differences. It is often suggested that participants receive a copy of the description

[2] Example of PQMethod software can be found at http://www.lrz.de/~schmolck/qmethod/
[3] Details of the online system FlashQ can be found at http://www.hackert.biz/flashq/home/ and QAssessor at www.q-assessor.com

and interpretation of the social perspectives revealed by the Q survey they have participated in (Webler *et al.* 2009). This allows the participants to understand how many different group identities there are and how they interact with the particular phenomena with which they are involved. This may help participants to understand and learn about the other groups and their perspectives and subsequently improve relationships.

3.3.1 Application of Q Methodology Technique to the Research Problem

In order to investigate and obtain an understanding of different expert perceptions of hydrogen from waste and the role of the innovation system, initially the population in question had to be identified. This was done based on existing academic and grey literature and the activity of carrying out semi-structured interviews with a number of academic, government and business experts. The experts selected to participate in the initial interviews to form the concourse were identified as individuals already known to the EPSRC SUPERGEN XIV "Delivery of Sustainable Hydrogen" team at Cardiff University. The selected experts were contacted by email initially and then by telephone to arrange interviews. Participants were then grouped according to their influence on hydrogen production from waste activities in the UK. This process was replicated for individuals in waste management and policy and energy management and policy across the UK. With the organisations identified, they were contacted by telephone and email for a suggested contact. Identifying individuals actively engaged in hydrogen production from waste was challenging due to the immature nature of the sector. Pilot plants were only operating in research environments. In addition to known individuals, three additional participants were added using the 'snowball' method. The result was twelve participants for the initial interviews. All of the experts participated anonymously and signed a consent form. This process led to the identification of particular sectors where developments around hydrogen from waste, hydrogen technologies, waste management technologies and policy implementation were happening across the UK.

In this study the perceptions of the individuals identified were not based on their geographical location, but on their knowledge of the subject and their impact on the field of the sustainable production of hydrogen from waste. The Q methodology study focused on investigating the technological innovation system surrounding the sustainable production of hydrogen from waste. For this Q methodology survey it was accepted that not all participants would have a complete knowledge of all the issues that filter in to this one specific field. Contributions from the waste, transport, energy, hydrogen chemistry and regulatory elements from business, academia and government were included in the survey. The aim was to have representation from all the fields that contribute to the success or failure of hydrogen from waste innovation systems. The relationship of the Q methodology to the hydrogen from waste innovation system in the UK is given in Chapters 5 and 7.

3.3.1.1 Development of the Concourse

The statements for the Q-sorts were taken from a number of different sources that made up the concourse; these included academic and grey literature, seminars and, as noted above, twelve semi-structured interviews which were conducted with experts in the fields of hydrogen futures, waste management, hydrogen technologies and energy management. The study population interviewed as part of the concourse development was made up from people in the sectors shown in Table 3.3.

The questions for the initial interviews were developed based on existing academic literature relating to hydrogen futures and technological innovation systems, and are shown in Box 3.2 below. The questions aimed to address the functions of innovation and identify drivers, barriers and relationships that may be occurring within the hydrogen from waste field (see sections 2.4 and 2.6). The interviews were conducted face-to-face and were designed to draw out the participant's views and opinions on hydrogen production from waste and its associated innovation system. Cardiff University's School of Architecture Ethics Committee approved the interview questions. Interviews were carried out between April and September 2011.

Table 3.3. The study population for expert interviews to develop concourse.

SECTOR	MALE	FEMALE
Energy Researchers	1	1
Hydrogen production academics	1	1
Energy professionals and policy advisors	3	0
Industrial gas professional	0	1
Waste management and policy	2	1
Other (e.g. Non-governmental Organisations, Regulators and independents)	1	0
Total	8	4

Interview Questions: Initial Interviews

1. *Please could you briefly outline your position and role?*
2. *Could you please describe in as much detail as you can your experience of energy from waste?*
3. *There are contested views on creating hydrogen as a fuel for the future. Currently technology exists to create hydrogen from fossil fuels and through electrolysis. Methane can be created from waste processes and can be used to fuel vehicles and create energy more simply than hydrogen. It has been suggested that it adds an additional process, uses more energy and may not be cost efficient. What are your views on creating a hydrogen based society in the future?*
4. *How does creating hydrogen as a fuel for energy fit into your experience of energy from waste?*
5. *When you think about hydrogen production from waste what scenario do you think it could be used in?*
6. *Do you know of any particular technologies currently used that can produce hydrogen from waste? Can you describe them?*
7. *Thinking about the future are you aware of any technologies that could be used to produce hydrogen from waste that are not currently available?*
8. *Can you describe in as much detail as possible which individuals, actors or organisations would be involved in making hydrogen production from waste a realistic scenario in the future? Do you work with anyone directly involved in this field?*
9. *When you think about sustainability, how does energy from waste fit into your vision of sustainable development? Can you explain what aspects of SD it does or doesn't fit with.*
10. *When you consider using hydrogen as a fuel created from waste, does your vision of sustainable development change? If yes which aspects?*
11. *Is there anything else you would like to add?*

Box 3.2. Semi-structured interview questions for Q methodology.

These initial interviews were all carried out in person at the participant's place of work or at seminars and conferences where interviews were possible. Seven out of the twelve participants went on to take part in the full Q methodology survey.

Initially over 250 relevant statements were generated from these different concourse sources, providing insights into the many different perspectives surrounding this field. The concourse was sorted into five themes covering:

- Energy from waste and waste management
- Energy and innovation policy
- Sustainable energy futures
- Hydrogen technologies
- Risk and public acceptability

Working with the EPSRC SUPERGEN XIV "Delivery of Sustainable Hydrogen" team at Cardiff University the more than 250 statements were reduced to thirty-five, ensuring that the emerging discourses were captured with the most valuable statements from the themes. In the first stage of selecting the statements, duplicate or weaker statements that could not be easily interpreted or were considered overly complicated were removed.

3.3.1.2 Development of Q-Sort

The Q-sort of these thirty-five statements was conducted with twenty-five experts, including, as noted, seven of the twelve interviewed during the development of the concourse. The P-set included professionals who are energy researchers, hydrogen production academics, energy professional and policy advisors, industrial gas professionals, waste management and policy professionals, other NGOs. The statements used for the Q-sort are shown in Table 3.4. The statements for the Q-sort were randomised and numbered.

Table 3.4. Statements produced from discourse for Q-sort.

Theme 1: Energy from waste and waste management
31. Waste is a great potential energy source.
20. The economics do not exist to justify hydrogen from waste.
10. Hydrogen must be created in a big plant to make it worthwhile.
21. The inhabitants of a village or town can directly benefit from making fuel from their waste.
15. If energy from waste is taken to a point that it is so efficient it will de-incentivise reducing and recycling materials.
25. The waste hierarchy needs to be revisited and made more holistic.
6. Energy from waste should be a point of last resort.
Theme 2: Energy and innovation policy
29. UK must keep pace with hydrogen developments in Germany, Japan and the US.
18. The bureaucracy in the UK government system is a huge barrier to emerging technologies.
34. If there were real impetus from the automotive industry the production of hydrogen would happen more quickly.
33. Without incentives hydrogen production plants will never get built.
22. The input and resources put into creating networks is greater than the economic output.
4. Companies must see hydrogen from waste as a credible market.
3. An innovation system around hydrogen from waste needs to be developed to keep hydrogen on the table.
11. Hydrogen use for fuel is not yet close to market development.
28. There must be a market to produce hydrogen.
35. Currently renewables are locked out of the energy system.
Theme 3: Sustainable energy futures
12. Hydrogen will have a large role in a future energy system.
13. Hydrogen will have no role in a future energy system.
1. 10% of world energy might come from waste.
32. We have a gas grid we could use for hydrogen.
19. The development of a hydrogen system will happen independently of whether the hydrogen is generated from waste.
Theme 4: Hydrogen technologies
14. Hydrogen will play a very significant and critical role in storing energy.
9. Hydrogen is a fuel for now.
17. Raw biogas contains the very contaminants that tend to damage catalysts.
2. Advanced plasma gasification works well for producing hydrogen from waste.
5. Dark fermentation followed by anaerobic digestion is a good method of producing methane and hydrogen.
26. There is not the energy payback to justify producing hydrogen.
Theme 5: Risk and public acceptability
27. There is risk involved in any technology.
16. Producing hydrogen locally can overcome negative perceptions of hydrogen.
23. The public do not understand the concept of making hydrogen from waste.
24. Environmental, social and economical impacts must be considered when making decisions about hydrogen.
30. Waste and energy professionals do not share a common language.
7. Face-to-face communication is best for hydrogen.
8. Fukushima has shown how explosive hydrogen can be.

3.3.1.3 Identification of Study Group

The Q-sorts were carried out between March and May 2012. The participants were identified as described in section 3.3.1.1. Table 3.5 provides gender and professional information on the cohort. Six of the initially selected participants were either unavailable or unwilling to take part and replacements were sought. As noted, the P-set is usually designed to be smaller than the number of statements. In this case, meeting that requirement meant providing between four and six participants to represent each viewpoint represented by the themes in Table 3.2 (van Excel & de Graff 2005). In this instance, this was not always achievable, but it was aimed for; the sectors in which the participants are active are shown in Table 3.5; these sectors address the themes in Table 3.4.

Table 3.5. Outline participant demographic.

Sector	Male	Female
Hydrogen Futures	**3**	**0**
Hydrogen Technologies	**7**	**1**
Energy Policy	**3**	**2**
Waste management and policy	**3**	**2**
Other (e.g. Non-governmental Organisations, Regulators and independents)	**4**	**0**
Total	**20**	**5**

Table 3.5 shows that the majority of participants were male; this is likely to be a reflection of the sector demographics. The largest group participating was from the hydrogen technologies group, encompassing chemistry (catalysts, membranes and electro chemistry) as well as those working in the energy industry. The group entitled “Other” provided input from national environmental regulators, hydrogen advocacy and chemical engineering. All of the participants were working directly in fields that relate to the sustainable production of hydrogen from waste.

3.3.1.4 Data collection procedure

Participants were contacted by email and telephone and, as noted, the majority of surveys were carried out at their place of work, or at group meetings and conferences.

Participants were asked to sort 35 cards with the statements on with the following guidance:

"Please complete the survey based on your view of hydrogen production from waste now and into the future with -4 being least like how you think/ feel and +4 being most like how you think or feel."

An additional request was given at the time of the Q-sort to *"Base your sort on what you believe to be most important."* This request was added as many of the statements would be agreeable to all participants, however, not necessarily of greatest importance depending on their interpretation or knowledge of the statement and the sector they represented. Participants were asked at the time of the survey to provide their personal view and not that of the organisation they worked for. All Q surveys were audio recorded using a digital Dictaphone and transcribed by the Cardiff based company Transcribe This.

The Q-sorts were carried out by hand by the participants, who placed them onto an A1 sheet of paper following the Q convention of 'forced normal distribution' with the central column being neutral. Figures 3.2a & 3.2b show the distribution layout as well as pre and post sort photos. Following the sort, the distribution was recorded both photographically and by recording the statement numbers directly onto the sort layout sheet.

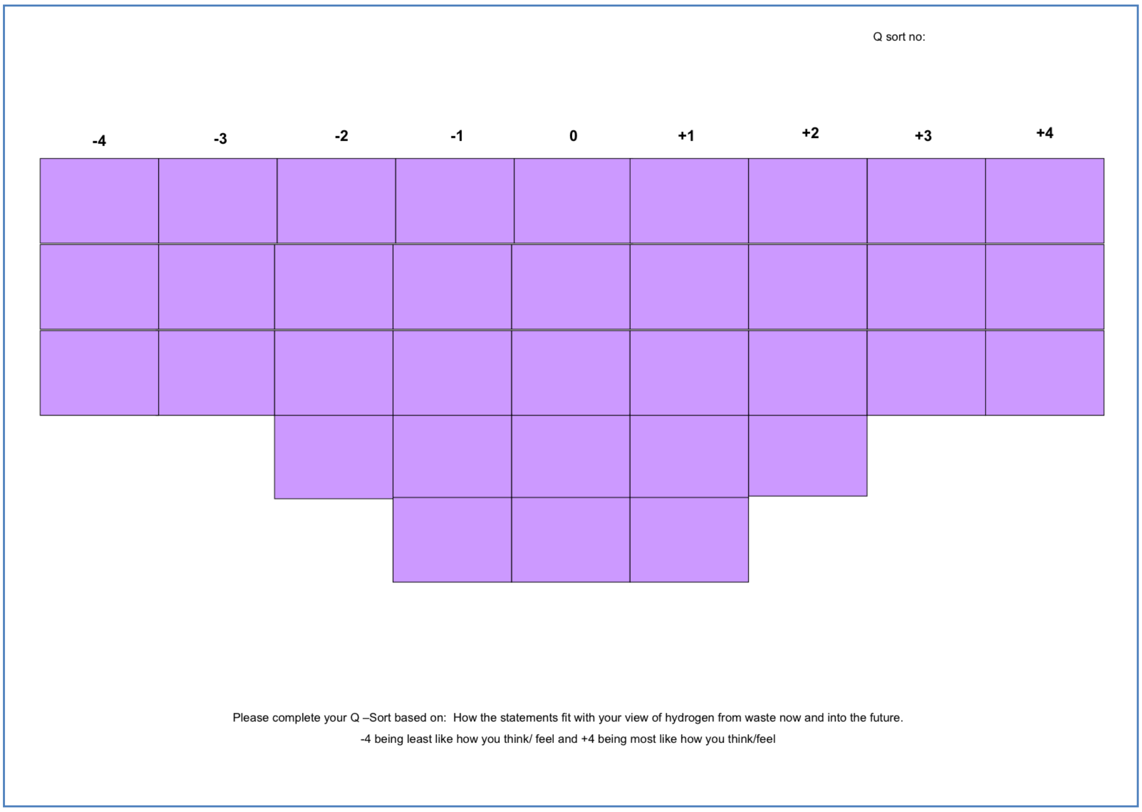


Figure 3.2a. Q-methodology sort board before completion.

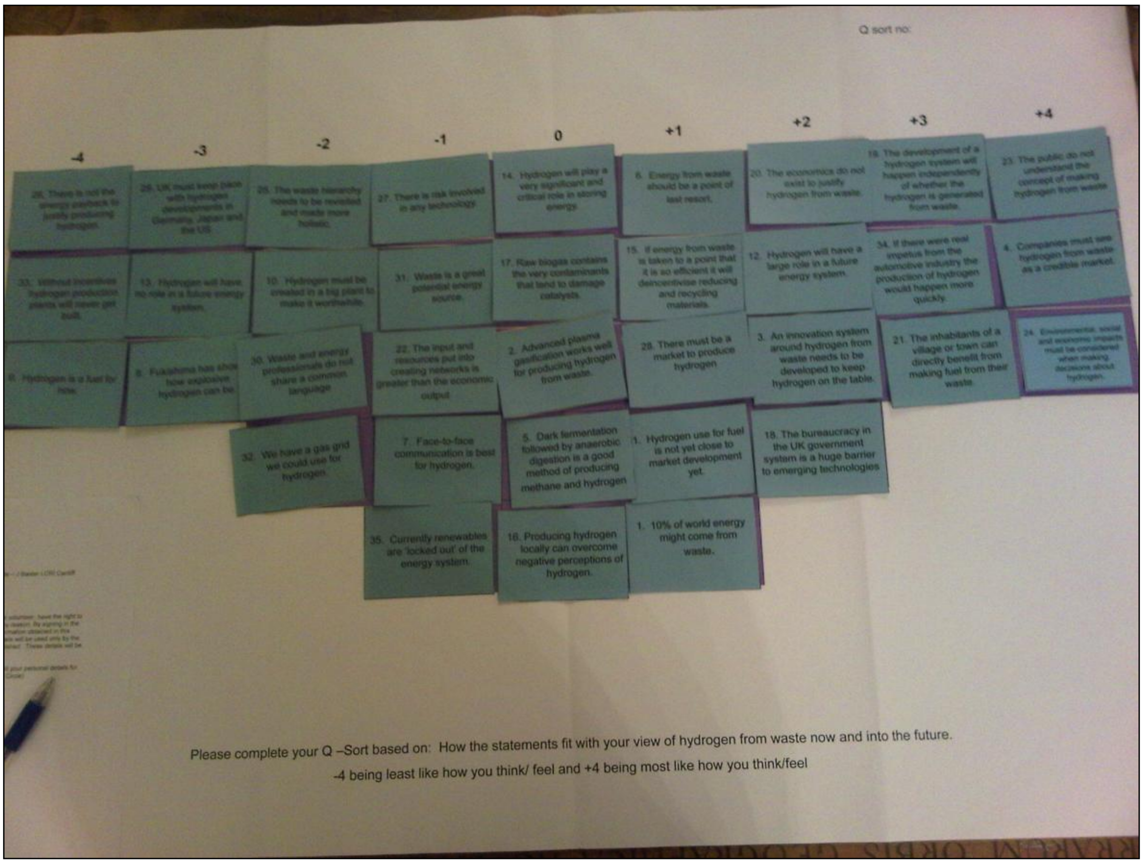


Figure 3.2b. Example of a Q methodology board after completion.

3.3.1.5 Data Analysis

Analysis of the data was carried out using PCQ analysis software[4]. This provided a screen view very similar to the raw data, enabling all twenty-five Q sorts to be entered and analysed. The software uses a statistical process called factor analysis to produce factors that can be thought of as "centres of gravity" or "centroids"; the centre of gravity is the average of the relationship between all sorts from which the different identities can be developed. Once these factor "centroids" had been produced, a varimax rotation was carried by the PCQ software to identify sorts that had the greatest association with each factor. The varimax rotation is a strictly mathematically process that produces the significance level. The varimax rotation ensures that the variance is distributed across all factors and all sorts, subsequently producing the significance level. The significance levels determine which factor a particular sort is most closely related to. All sorts meeting or exceeding the identified significance level have a close association with one of the factors (PCQ 2012).

3.3.1.6 Interpretation and Construction of Factor Identities

Once the factors were produced, all statements relating to each factor were sorted and related to each of the factors analysed. The results of three factors were interpreted and compared to each other. A commentary and discussion of their contribution to technological innovation systems was developed.

The results of the Q methodology and the construction of the identities can be found in Chapter 4.

[4] The PCQ software was purchased from WoodsStrickland http://www.pcqsoft.com/

3.4 Rock Engineering Systems (RES) Model

In section 2.6, conceptual models for sustainable transitions, innovation systems and functions of innovation were presented and critiqued. This review covered a number of different approaches to understanding the technological innovation system as a means to aiding the development of technological transitions. It has shown that many methodologies have been tested through different applications. The methods described, however, do not address the relationships between the different functions of innovations. In addition, very few address these relationships through the use of participation (interviews and surveys). The studies presented covering functions of innovation also demonstrate a lack of consideration of relationships between the functions. It is suggested that this lack of consideration of relationships between functions of innovation is preventing studies moving beyond describing only the barriers and blocking mechanisms involved in a TIS. The RES method presents an opportunity to consider how interactions between the different functions could be harnessed to move technologies closer to commercialisation. The literature presented in section 2.6 also suggests that there is a need for further development through new combinations of schemes of analysis and conceptual frameworks.

With the above in mind, a method for analysing innovation systems is presented here using Temel *et al.* 2003) as an example. This RES methodology applied to, in this instance, agricultural innovation systems (another form of sectoral innovation systems) formed the basis for the model developed for this research. The new model and its application to UK case studies are presented in Chapter 5. Currently this is the only existing study that uses the RES model to analyse innovation systems.

The RES methodology provides a model that ensures that all the interactions between the different variables and parameters in a project are fully explored and understood (Hudson 2013). The RES methodology brings cohesion to the variables and parameters and guides the investigator through the interactions to a desired outcome.

The RES method is presented here as a suitable option for analysing emerging technological innovation systems for the sustainable production of hydrogen from waste in the UK. The RES will provide results that may be interpreted in order to influence further development of emerging systems, as well as policy development.

In the following section a review of a specific RES application is provided. This study was conducted by Temel Tugrul, a senior research fellow at Tilburg University in the Netherlands (Temel *et al.* 2003). Temel has a particular interest in innovation systems and policy, particularly relating to agriculture. This review aims to provide a comprehensive view of how the RES method can be used to identify relationships within a technological innovation system and their significance to each other and the system as a whole. Details of other RES applications are provided in section 3.4.1.

Temel *et al.* (2003) present an interactive matrix approach to analysing agricultural innovation systems. It is suggested that this may be easily transferable to TIS. In their study a mixed methods approach is used that brings participation and innovation systems together. They describe this methodology as promising wide applications among policy makers who are interested in assessing alternative innovation policies and/or programmes by identifying effective pathways of interactions between the components and the constraints that hinder these interactions. In their assessment of institutional linkages in agricultural innovation systems, another form of sectoral innovation system, Temel *et al.* (2003) presented the use of a model previously used primarily to assess engineering and science based problems. Their study does not draw upon the functions of innovation literature, but does utilise literature on innovation systems such as (Freeman 1987).

The rock engineering systems (RES) model is an interactive matrix that presents the key components or subject areas to be analysed in the central diagonal of the matrix. In this case it is the components of the agricultural innovation system in Azerbaijan as identified through interviews with key stakeholders, shown in Table 3.6.

Components	Number of persons interviewed
Policy	7
Research	12
Education	5
Credit	1
Extension and information	4
Inputs-processing-outputs marketing	8
Farm organizations	10
Private consultancy	11
External assistance	5
Total	63

Table 3.6. Details of the agricultural system components and the number of Individuals interviewed in order to analyse them in detail (Temel *et al.* 2003).

These components are presented in the diagonal of the interaction matrix as shown in Figure 3.3 as PRIFX. The five diagonal components are: Policy (P), Research (R), Information (I), Farm organization (F) and External assistance (X). Later in their study the matrix is increased to include all components shown in Table 3.6.

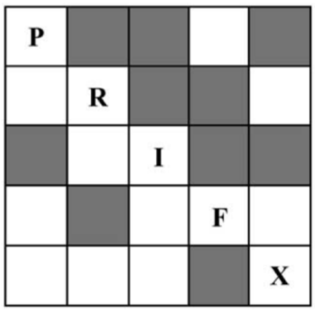


Figure 3.3. The basic interactive RES matrix (Temel *et al.* 2003).

The outer boxes represent the interactions and relationships occurring in the innovation system. In their paper Temel *et al.* (2003) analysed the cause and effect implications of the system components upon each other, and so were able to establish how the different innovation system components influenced each other. They concluded that the results suggested that ample scope exists for the design and implementation of linkage mechanisms among the components of the innovation system (Temel *et al*. 2003).

3.4.1 Temel Tugrul RES Application Review (Temel *et al* .2003)

In a recent review paper Hudson (2013) brings together all the different applications of the RES matrix over the past twenty years. The review shows that to-date there is only one previous application of the RES matrix to an innovation system problem. In this instance it was the analysis of the innovation system surrounding agriculture in Azerbaijan produced by (Temel *et al.* 2003).

In this section a detailed review of the activities that Temel *et al.* (2003) undertook is provided and the relationship with the Interaction Matrix-Technological Innovation System IM-TIS model explained. However, the functions incorporated in the IM-TIS model differ from those considered by Temel *et al.* (2003). These differences are described in Chapter 5, the development of the IM-TIS model. This review refers both to (Temel *et al*. 2003), a peer reviewed paper, and the associated report (Temel *et al*. 2002), which is considerably more detailed than the published paper. A broader review of the RES method and its applications outside the field of innovation systems is given in section 3.4.2.

Temel *et al*. (2003) describe the RES model as offering "wide applications among policy makers who are interested in assessing the alternative innovation policies and/or programs identifying effective pathways of interactions between the components and the constraints that hinder these interactions". It was this statement that provoked particular interest in extending the approach to assess the effectiveness of emerging innovation systems for hydrogen from waste in the UK.

They began their work on the analysis of the Azerbaijan agricultural innovation system (AIS) in 1997 with three primary aims:

1. Describe and analyze the main components of the AIS of Azerbaijan;
2. Identify the main priorities that the public-sector components of the AIS should address, in light of what the private-sector components of the AIS are expected to do, and

3. Recommend changes in the functioning of the public-sector components to increase the effectiveness of the AIS (Temel *et al*. 2002).

These aims were approached by using the qualitative information obtained from surveys sent to key individuals working in or influencing the Azerbaijan AIS, to inform a number of different theoretical analysis methods.

Of particular interest is the description provided by Temel *et al.* (2003) of the linkage matrix. This matrix maps cross-component linkages relating to a specific goal. In this instance, to develop, diffuse and apply new or improved technologies associated with the AIS. Figure 3.4 illustrates the basic AIS linkage matrix called AISA. The matrix consists of five components represented by the letters PRIFX, seen here in the principal diagonal positions. Relationships between these components are represented in the off-diagonal positions in the matrix. The number of components was increased later in the investigation (Temel *et al*. 2003) due to the number of factors generated from the questionnaires that were considered main components of the AIS. The full matrix showing all diagonal components and relationships is provided in the portfolio complementing this thesis.

The five diagonal components are: Policy (P), Research (R), Information (I), Farm organization (F) and External assistance (X). The linkages follow a clockwise convention and the relationships are shown in the off-diagonal positions. For example, the term PR in the first row, second column indicates the influence that policies would have on research. The reverse of this relationship is shown by RP in the second row of the first column and is the influence that research may have on policy development.

$$
\mathbf{S} = \begin{bmatrix} \mathrm{P} & PR & PI & PF & PX \\ RP & \mathrm{R} & RI & RF & RX \\ IP & IR & \mathrm{I} & IF & IX \\ FP & FR & FI & \mathrm{F} & FX \\ XP & XR & XI & XF & \mathrm{X} \end{bmatrix}.
$$

Figure 3.4. The linkage matrix AISA developed by Temel *et al.* (2003)

Temel *et al*. (2003) also identify pathways between matrix positions. For example, it is possible to move through the matrix from P and R via I and F. This is described as a three-edged pathway, where the edges are indicated by the intermediary interactions. This can be achieved as follows:

P»PI»I»IF»F»FR»R.

There are many possible pathways between diagonal components within the matrix and these may be followed to achieve particular outcomes in innovation, particularly when a direct relationship does not exist. The number of edges in the pathway is defined by (n-1) where n denotes the number of components in the matrix. In the example given in Figure 3.4 n=5 (n being the number of primary subjects) therefore possible edges to the pathways in this matrix = 4 (Temel *et al*. 2003).

In order to develop the components of the applied AISA matrix, Temel *et al*. (2003) gathered data using a questionnaire and from these expanded their initial matrix to include nine components. These data can be found in (Temel *et al.* 2002) and form the basis for both Temel *et al*. (2002) and (2003). The nine components identified were:

- Policy (P)
- Research (R)
- Education (E)
- Credit (C)
- Extension and information (I)
- Inputs-processing-outputs marketing (M)
- Farm organizations (F)
- Private Consultancy (D)

- External Assistance (X)

These components formed the principal diagonal of the matrix and the cause-effect linkages between the components were developed. Once the linkages were described they were placed into the matrix and coded based on the experts' assessment of how formal/informal and weak/strong the system is. Further details of this matrix can be found in the portfolio accompanying this thesis.

The matrix was then reconstructed using a 0-3 coding structure, where 0 shows no influence between the components and 1 for weak, 2 for medium and 3 for strong influence. From this a cause-effect graphical representation of the system was formed establishing the dominant and subordinate components within the matrix.

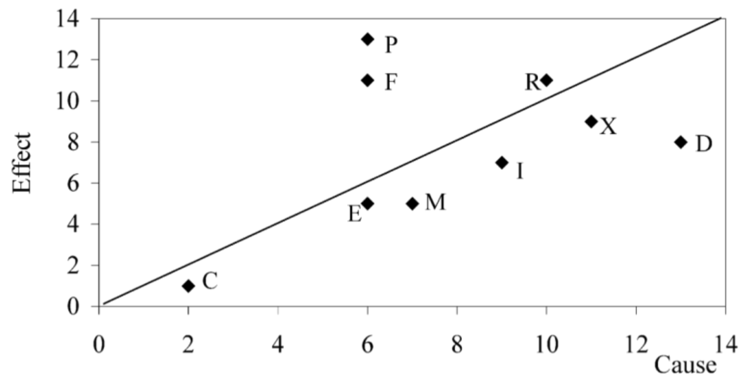


Figure 3.5. The cause and effect graphical representation of AISA (Temel *et al*. 2003).

Components shown beneath the cause-effect line are dominant and those above the line subordinate. Component D (Private Consultancy) dominates the whole system and is a highly interactive component, as it appears closer to the maximum strength of 14. However, component C (Credit), seen at the lower end of the system, has almost no interaction with the other components. Furthermore, components seen above the line P (policy), F (farm organisation) and R (research) are subordinate to the other components in the system.

From the matrix development and subsequent coding and graphical representation, Temel *et al*. (2003) were able to establish a number of pathways that positively influence the AIS or inform policy makers and regulators of agriculture in Azerbaijan.

In addition, they were able to say where additional regulation, policy, research or financial support may be required in order to achieve desired outcomes. They concluded that the graph-theoretical concept is especially useful for examining the interactive nature of AISA (Temel *et al*. 2003).

Temel *et al.* (2002; 2003) provide a basis for further developing the use of the interaction matrix to inform innovation systems policy and application. The papers show how linkages can be made between key components in policy development and real life situations, and how these linkages can be classified in terms of importance to the system requirements. The cause and effect representation of the matrix provides an opportunity to identify gaps or difficulties within the system, as well as overbearing components that may need to be more heavily controlled. All of these elements are essential elements of innovation and may be found in the functions of innovation concept. The process of combining functions of innovation with RES is judged a sound basis for the analysis of the technological innovation system for hydrogen production from waste in three case study regions in the UK.

The following section provides a general literature review of the RES method and its application to non-innovation based studies.

3.4.2 General RES Method Literature Review.

In their recent review paper Hudson *et al.* (2013) state that a critical aspect of rock engineering modelling and rock engineering design is ensuring that all the necessary variables have been included and that interactions between them are understood. It is here that RES provides a guiding methodology. This concept of understanding the interactions between the variables that can assist problem solving provides the basis of the method being transferred to the RES-TIS methodology presented in Chapter 5.

The RES methodology was first developed and used twenty years ago (Hudson 1992) to understand relationships between the main parameters affecting a particular issue/ problem area in rock engineering. Initially the applications for RES were in areas such as mining, blasting, slope stability, and underground stability and support (Hudson

2013). In reviewing the two decades of applications for the RES, Hudson (2013) reports on how RES has diversified to some extent beyond rock engineering.

Hudson (2013) reviewed the significant applications of RES. Thirty-three different applications were identified of which only four are not related to rock engineering or groundwork engineering problems. These four applications are considered in this literature review as having more in common with the sustainable production of hydrogen from waste than the engineering applications. The studies are shown in Table 3.7.

Table 3.7. Non-engineering RES studies.

RES studies (non-engineering)
Avila R., Moberg L. A systematic approach to the migration of ^{137}Cs in forest ecosystems using interaction matrices. Journal of Environmental Radioactivity 45 (1999) 271–282
Mavroulidou M., Hughes S.J., Hellawell E.E. A qualitative tool combining an interaction matrix and a GIS to map vulnerability to traffic induced air pollution. Journal of Environmental Management 4 (2004) 283-289
Mavroulidou M., Hughes S.J., Hellawell E.E. Developing the interaction matrix technique as a tool assessing the impact of traffic on air quality. Journal of Environmental Management (2007) 513–522
Temel, T., Janssen W., Karimov F. Systems analysis by graph theoretical techniques: assessment of the agricultural innovation system of Azerbaijan. Agricultural Systems 77 (2003) 91–116 *(Temel* et al*. (2003) has been reviewed section 3.4.1)*

In their 1999 study of the migration of ^{137}Cs in forest eco-systems, Avila & Moberg (1999) identify the use of the RES matrix as a process that ensures that important components and interactions are not omitted or underestimated. The RES is used to represent the mechanisms responsible for the behaviour of the system. Avila & Moberg (1999) state that while forming a conceptual model is an early stage in forming a mathematical model, the conceptual model may have meaning of its own. A matrix was created using five initial variables, identified from the authors' own knowledge and existing literature. As the study progressed, further, variables were added, creating a nine by nine matrix. The matrix was coded using an expert semi-quantitative system and this helped to produce the conceptual model. In this study it was important to identify the migration pathways, which were combinations of multiple interactions in the system. Consequently, the study starts with the assumption that interactions between component variables are possible, and that identifying dominant pathways through the interactions is beneficial. The other steps in the RES method were then carried out, identifying cause and effect relationships within the system. The study presents the knowledge gained from this investigation. The authors conclude by stating that this method can be used as a tool for ecological studies.

The following two studies are products of the same research group. The first paper (Mavroulidou *et al.* 2004) introduces the process for developing a tool for performing initial air quality assessments. RES is applied in this study as an alternative to the increasing costs associated with complex numerical modelling. RES provided an option that was faster and less complicated to apply, yielding an initial assessment of the air quality situation. The investigation presents the development of a tool that combines RES with environmental impact assessments (EIA). The authors describe the results of this combination as highly visual and readily understandable by non-specialist public and decision makers. First the interaction matrix was developed; in this case its dimensions were seven by seven with forty-two possible interactions or relationships between primary subjects. This study developed a cause-effect graph and identified the dominant and subordinate variables in the system. The study also indicates that the interaction model developed could be used to perform “what if” scenarios. These scenarios could assist transport planners in identifying areas where air quality may be compromised. The authors conclude that the method is very useful in conceptualising the system, and identifying the contribution to the overall system behaviour/ structure made by particular parameters or variables.

In their second paper Mavroulidou *et al*. (2007) develop the interaction matrix approach in order to quantify the variables that contribute to air pollution from traffic. In this study the method is divided into five phases:

1. Selection of key system variables
2. Assignment of variable relationships
3. Quantification of the matrix values
4. Calculation of weighting values

5. Development of vulnerability maps using geographical information systems (GIS)

This study also combines the RES technique with another system, i.e. a Geographical Information System (GIS). The use of semi-empirical relationships was introduced; this new coding was considered more flexible than that in their previous model (Mavroulidou *et al.* 2004). The interaction matrix designed in this study was applied to a region of Surrey known to have significant traffic congestion. The results from this study showed that the interaction matrix can address combinational or multi-disciplinary problems involving the interaction of multiple variables.

These studies demonstrate that RES combines well with other conceptual models and established information systems. The model provides an assistive tool that supports complex multidisciplinary problems; this is of particular relevance in this research project.

Hudson (2013) concludes that as a result of the RES studies conducted over the last twenty years, many developments have been made. It is anticipated that combinations of RES with other models (particularly artificial neural networks) will be made.

3.5 Summary

In this section the two primary methods being applied to the research problem have been presented. The Q methodology will seek to understand in more detail how experts involved in technological innovation around hydrogen production from waste view the role of hydrogen in a future energy system. It will also aim to extract identities for these experts and further explore their relationships with each other and their impact on innovation in this research field.

The RES methodology provides the interactive and dynamic elements in a model that can be applied to technological innovation systems. As noted above, RES combines well with other conceptual models. This has led to the development of a new interaction matrix model, IM-TIS, that amalgamates the RES matrix with the functions of innovation framework (Bergek *et al.* 2008). The process of this development and two applications are given in Chapter 5.

3.6 References

Avila R., Moberg L. A systematic approach to the migration of ^{137}Cs in forest ecosystems using interaction matrices. Journal of Environmental Radioactivity 45 (1999) 271–282

Balat H., Kirtay E. Hydrogen from biomass – Present scenario and future prospects. International Journal of Hydrogen Energy 35 (2010) 7416–7426

Balat M., Potential importance of hydrogen as a future solution to environmental and transportation problems. International Journal of Hydrogen Energy 33 (2008) 4013–4029

Barker, J.H. 2008. 'Q-methodology: An alternative approach to research in nurse education'. Nurse Education Today 28: 917-925.

Barry J., Proops J. Seeking sustainability discourses with Q methodology. Ecological Economics 28 (1999) 337–345

Bergek A., Jacobsson S., Carlsson B., Lindmark S., Rickne A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (2008) 407–429Brown S, Political subjectivity: Applications of Q methodology in political science. New Haven, CT: Yale University Press. 1980

Bracken, S.S. and Fischel, J.E. 2006. 'Assessment of preschool classroom practices: Application of Q-sort methodology'. Early Childhood Research Quarterly 21: 417-430.

Brown, S.R. (1980). Political subjectivity: Applications of Q methodology in political science. New Haven, CT: Yale University Press

Bryant, L.D., Green, J.M. and Hewison, J. 2006. 'Understandings of Down's syndrome: A Q methodological investigation'. Social Science & Medicine 63: 1188-1200.

Butler, M.G., Schumock, G.T., Wilken, L., Jaffe, H.A. and Mrtek, R. 'PAA15 Iinvestigation of the determinants of adherence in asthma using q Q methodology'. Value in Health 7: 313-314.

Chang, S.O., Kim, J.H., Kong, E.S., Kim, C.G., Ahn, S.Y. and Cho, N.O. 2008. 'Exploring ego-integrity in old adults: A Q-methodology study'. International Journal of Nursing Studies 45: 246-256.

Chinnis, A.S., Paulson, D.J. and Davis, S.M. 2001. 'Using Q methodology to assess the needs of Emergency Medicine support staff employees'. Journal of Emergency Medicine 20: 197-203.

Cross-Sudworth, F., Williams, A. and Herron-Marx, S. 'Maternity services in multi-cultural Britain: Using Q methodology to explore the views of first- and second-generation women of Pakistani origin'. Midwifery, In Press, Corrected Proof

Cuppen E. A quasi-experimental evaluation of learning in a stakeholder dialogue on bio-energy. Research Policy 41(2012) 624–637

Cuppen E. 2009. *Putting Perspectives into Participation: Constructive Conflict Methodology for problem structuring in stakeholder dialogues.* PhD Thesis, Vrije Universiteit Netherlands

Cuppen, E., Breukers, S., Hisschemöller, M. & Bergsma, E. 2010. 'Q methodology to select participants for a stakeholder dialogue on energy options from biomass in the Netherlands'. Ecological Economics 69: 579-591.

Curry R., Barry J., McClenaghan A. Northern Visions? Applying Q methodology to understand stakeholder views on the environmental and resource dimensions of sustainability. Journal of Environmental Planning and Management. 2012 10.1080/09640568.2012.693453

Davies B.B., Hodge I.D., Exploring environmental perspectives in lowland agriculture: A Q-methodology study in East Anglia, UK. Ecological Economics 61 (2007) 323–333

Doody D.G., Kearney P., Barry J., Moles, R., O'Reagan B. Evaluation of the Q-method as a method of public participation in the selection of sustainable development indicators. Ecological Indicators 9 (2009) 1129–1137

Dryzek J.S., Berejikian J. (1993) American Political Science Review. Pages 40-60. American Political Science Association.

Duenckmann F. The village in mind: Applying Q-methodology to reconstructing constructions of rurality. Journal of Rural Studies 26 (2010) 284–295

Exel, J.v., Graaf, G.d. and Brouwer, W. 2007. 'Care for a break? An investigation of informal caregivers' attitudes toward respite care using Q-methodology'. Health Policy 83: 332-342.

Frantzi S., Carter N.T., Lovett J.C. Exploring discourses on international environmental regime effectiveness with Q methodology: A case of the Mediterranean Axtion Plan. Journal of Environmental Management 90 (2009) 177–186

Freeman R E (19874). Strategic Management – A stakeholder Approach. Pitman Publishing Inc. ISBN 0-273-01913-9

Gee J.P. An introduction to discourse analysis theory and method. Routledge. 1999.

Harrison J.P., Hudson J.A. Comprehensive hazard identification in rock engineering using interaction matrix mechanism pathways. The 41st US Symposium on Rock Mechanics. 2006

Hekkert M.P., Suurs R.A.A., Negro S.O., Kuhlman S., Smits R.E.H.M., Functions of innovation systems: a new approach for analysing technological change. Technological Forecasting and Social Change 74 (2007) 413–432

Herron-Marx, S., Williams, A. and Hicks, C. 2007. 'A Q methodology study of women's experience of enduring postnatal perineal and pelvic floor morbidity'. Midwifery 23: 322-334.

Higgins J. The Correlation Coefficient. Chapter 2. Excerpted from The Radical Statistician by Jim Higgins, Ed.D. Accessed online 19/04/2013. http://www.nicholas.duke.edu/people/faculty/maguire/q-methodology.pd

Hudson J.A. 2013. A review of Rock Engineering Systems (RES) applications over the last 20 Years. In: Rock Characteristion, Modelling and Engineering Design Methods. (Eds. J.A. Hudson, X.T. Feng, Tan F.): Proc SINOROCK2013 ISRM Symposium, Shanghai, China, June 2013.

Jedeloo, S., van Staa, A., Latour, J.M. and van Exel, N.J.A. 2010. 'Preferences for health care and self-management among Dutch adolescents with chronic conditions: A Q-methodological investigation'. International Journal of Nursing Studies 47: 593-603.

Lachman D.A. A survey and review of approaches to study transitions. Energy Policy 58 (2013) 269–276

Markard J., Raven R., Truffer B. Sustainability Transitions: An emerging field of research and its prospects. Research Policy 41 (2012) 955–967

Mavroulidou M., Hughes S.J., Hellawell E.E. A qualitative tool combining an interaction matrix and a GIS to map vulnerability to traffic induced air pollution. Journal of Environmental Management 4 (2004) 283-289

Mavroulidou M., Hughes S.J., Hellawell E.E. Developing the interaction matrix technique as a tool assessing the impact of traffic on air quality. Journal of Environmental Management (2007) 513–522

Militello, M. and Benham, M.K.P. 2010. '"Sorting Out" collective leadership: How Q-methodology can be used to evaluate leadership development'. The Leadership Quarterly 21: 620-632.

Morecroft, C., Cantrill, J. and Tully, M.P. 2006. 'Individual patient's preferences for hypertension management: A Q-methodological approach'. Patient Education and Counseling 61: 354-362.

Niemeyer S., Petts J., Hobson K. Rapid climate change and society: Assessing Responses and Thresholds. Risk Analysis (25) 6 (2005) 1443-1456

Oring, K.E. and Plihal, J. 1993. 'Using Q-methodology in program evaluation: A case study of student perceptions of actual and ideal dietetics education'. Journal of the American Dietetic Association 93: 151-157.

Parker, J. and Alford, C. 2010. 'How to Use Q-Methodology in Dream Research: Assumptions, Procedures and Benefits'. Dreaming 20: 169-183.

PCQ Method Software – Website Accessed online March 2012

PCQ Users Guide. Analysis Software for Q Technique. Version 1.4.1 2001

Q Methodology Website accessed 17/04/2013 http://qmethod.org/links

Raje F. Using Q methodology to develop more perceptive insights on transport and social inclusion. Transport Policy 14 (2007) 4 467-477

Reed M.S., Graves A., Dandy N., Posthumus H., Hubacek K., Morris J., Prell C., Quinn C.H., Stringer L.C. Who's in and why? A typology of stakeholder analysis methods for natural resourse management. Journal of Environmental Management 90 (2009) 1933–1949

Richards C, Blackstock K, Carter C. Practical approaches to participation – SERG Policy Brief 1. The Macaulay Institute (2007)

Risdon, A., Eccleston, C., Crombez, G. and McCracken, L. 2003. 'How can we learn to live with pain? A Q-methodological analysis of the diverse understandings of acceptance of chronic pain'. Social Science & Medicine 56: 375-386.

Robbins, P. and Kimberly, K.-L. 2005. 'Q Methodology' Encyclopedia of Social Measurement. New York: Elsevier.

Schamp, R.O., Chibnall, J., Peterson, D. and Van Landuyt, A. 2008. 'Lifetyles: Using Q-Methodology to Assess Quality of Life and Care Priorities in Frail Elders'. Journal of the American Medical Directors Association 9: B16-B17.

Steelman T. A., Maguire L.A., Understanding Participant Perspectives: Q methodology in National Forest management. University of Colorado at Denver. Date Unknown. Accessed Online 16/04/2013

Stenner, P.H.D., Dancey, C.P. and Watts, S. 2000. 'The understanding of their illness amongst people with irritable bowel syndrome: a Q methodological study'. Social Science & Medicine 51: 439-452.

Stenner, P.H.D., Cooper, D. and Skevington, S.M. 2003. 'Putting the Q into quality of life; the identification of subjective constructions of health-related quality of life using Q methodology'. Social Science & Medicine 57: 2161-2172.

Stephenson, W. 1980. 'Newton's Fifth Rule and Q methodology: Application to educational psychology'. American Psychologist 35: 882-889.

Stephenson W. Theory and methodology for esthetics. Journal of the International Society for the Scientific Study of Objectivity. Vol 28 No:1/2 (2005) 13–32

Suurs R.A.A., Hekkert M.P., Smits R.E.H.M. Understanding the build up of a technological innovation around hydrogen and fuel cell technologies. International Journal of Hydrogen Energy 34 (2009) 9639–9654

Temel T., Janssen W., Karimov F. The Agricultural Innovation System of Azerbaijan: An assessment of institutional linkages. ISNAR Country Report 64. (2002)

Temel, T., Janssen W., Karimov F. Systems analysis by graph theoretical techniques: assessment of the agricultural innovation system of Azerbaijan. Agricultural Systems 77 (2003) 91–116

ten Klooster, P.M., Visser, M. and de Jong, M.D.T. 2008. 'Comparing two image research instruments: The Q-sort method versus the Likert attitude questionnaire'. Food Quality and Preference 19: 511-518.

Thomas D.M., Watson R.T. Q-Sorting and Research: A Primer. Communications of the Association for Information Systems. Vol 8, 2002.

Tran T.A., Daim T. A taxonomic review of methods and tools applied in technology assessment. Technological Forecasting and Social Change, Vol 75, Issue 9 (2008) 1396-1405

Truffer B., Markard J., Binz C., Jacobsson S. Energy Innovation Systems. Structure of an emerging scholarly field and its future research ditrections. A literature review. Chalmers University, Gothenburg. EIS November. (2012).

van der Kerckhof M and Weiczorek A (2005). Learning and Stakeholder Participation in transition processes: Methodological considerations. Technical Forecasting and Social Change 72 (2005) 733–747

Van Excel N.J.A., de Graaf G., Rietveld P. Getting from A to B: Operant approaches to travel decision making. Journal of the International Society for the Scientific Study of Subjectivity (27) 4 (2004)

Van Excel N.J.A., de Graff G. Q methodology: A sneak preview. Erasmus MC, Institute for Medical Technology Assessment. Rotterdam. (2005) www.jobvanexcel.nl

Venables D., Pidgeon N., Simmons P., Henwood K., Parkhill K. Living with Nuclear Power: A Q-Method Study of Local Community Perceptions. Risk Analysis Vol. 29, No. 8, (2009) 1089–1103

Webler T., Danielson S., Tuler S. 2009. Using Q method to reveal social perspectives in environmental research. Greenman MA: Social and Environmental Research Institute. www.seri-us.org

Wittenborn, J.R. 1961. 'Contributions and current status of Q methodology'. Psychological Bulletin 58: 132-142.

Yeun, E. 2005. 'Attitudes of elderly Korean patients toward death and dying: an application of Q-methodology'. International Journal of Nursing Studies 42: 871-880.

Van de Kerkhof ., Wieczorek A. Learning and stakeholder participation in transition processes towards sustainability: Methodological considerations Technological Forecasting and Social Change 72 (6), (2005) 733-747

Hudson J. A. *Rock Engineering Systems-Theory and Practice*. Publ. Ellis Horwood, 1992, p.185

4 Analysis of expert perspectives using Q methodology: the construction of the identities of three groups of experts

In the previous Chapter, the methodology was presented. This included the Q methodology and the Rock Engineering Systems model. These methodologies were designed as a unique way to begin to address the research gaps identified in section 2.7. Particular gaps in the literature were found in relation to expert and professional perspectives around the sustainable production of hydrogen from waste. It was shown that the Q methodology provided an established discourse analysis technique that could address this issue.

Objective 2 presented in section 1.2 is: "*To characterise, using Q methodology, the different expert communities involved in the production of H_2 from waste in the UK and their role in the technological innovation system".* The results presented in this Chapter provide new findings from the application of the Q methodology that fulfil this objective.

This Chapter presents the results of the twenty-five Q methodology surveys. As noted earlier in the thesis, Q methodology, a form of discourse analysis, was conducted to explore the visions and perspectives of experts working in the technological field of hydrogen production from waste. Experts participating in the analysis were professionals working in hydrogen production, waste management, energy management and energy from waste. The process of applying a Q methodology is described in detail in Section 3.3.

This chapter begins in section 4.1 with a brief summary of the Q methodology and a reminder of the statements used to develop the identities. The Chapter then moves on to show the findings, including how each participant weighted the statements in the Q methodology survey, how many participants from each professional sector weighted particular statements, and which statements provide the make-up of the factor identity. In section 4.2, an analysis of three out of the nine factors produced is presented. In relation to these three factors, enough participants weighted statements on them to reveal three different identities. Some broad reflections on the possible effects that each identity may have on the technological innovation system are offered in section 4.4.2 (they are discussed in more detail in Chapter 8). Finally, in sections 4.3 and 4.4, the chapter reviews the Q methodology study's contribution to achieving the aims and objectives of the research; in addition, its limitations are discussed.

4.1 Summary of the Q methodology

As shown in section 3.2, Q methodology is an established approach having clearly defined steps to complete a Q methodology survey. Obtaining meaningful identities is the outcome of the Q methodology and this relies on the completion of all steps. These steps were as follows.

1. **Development of the Q sort** - twelve face-to-face interviews were conducted with experts working in hydrogen from waste and associated sectors. Statements from these interviews were extracted for use in the Q sort; the statements are given in Table 4.1. Further details of the interview process are given in section 3.3.1. In addition, statements from seminars and academic literature were also used in the Q sort.
2. **Identification of the study population** – experts were identified from the fields of hydrogen futures, hydrogen technologies, energy policy, waste management and policy, NGOs and regulators.
3. **Data collection –** twenty-five Q-sort surveys were carried out face-to-face and the results recorded in both hard copy and digitally.
4. **Data analysis** – The results were analysed using PCQMethod softwar**e**
5. **Production of factor identities** – three expert identities were uncovered: hydrogen from waste advocates, cautionary environ**m**entalists and hydrogen technologists (van Excel 2005).

Table 4.1 provides a reminder of the statements used in this Q methodology survey.

Table 4.1. Statements used in the Q sort.

Theme 1: Energy from waste and waste management
31. Waste is a great potential energy source.
20. The economics do not exist to justify hydrogen from waste.
10. Hydrogen must be created in a big plant to make it worthwhile.
21. The inhabitants of a village or town can directly benefit from making fuel from their waste.
15. If energy from waste is taken to a point that it is so efficient it will deincentivise reducing and recycling materials.
25. The waste hierarchy needs to be revisited and made more holistic.
6. Energy from waste should be a point of last resort.
Theme 2: Energy and innovation policy
29. UK must keep pace with hydrogen developments in Germany, Japan and the US.
18. The bureaucracy in the UK government system is a huge barrier to emerging technologies.
34. If there were real impetus from the automotive industry the production of hydrogen would happen more quickly.
33. Without incentives, hydrogen production plants will never get built.
22. The input and resources put into creating networks is greater than the economic output.
4. Companies must see hydrogen from waste as a credible market.
3. An innovation system around hydrogen from waste needs to be developed to keep hydrogen on the table.
11. Hydrogen use for fuel is not yet close to market development.
28. There must be a market to produce hydrogen.
35. Currently renewables are locked out of the energy system.
Theme 3: Sustainable energy futures
12. Hydrogen will have a large role in a future energy system.
13. Hydrogen will have no role in a future energy system.
1. 10% of world energy might come from waste.
32. We have a gas grid we could use for hydrogen.
19. The development of a hydrogen system will happen independently of whether the hydrogen is generated from waste.
Theme 4: Hydrogen technologies
14. Hydrogen will play a very significant and critical role in storing energy.
9. Hydrogen is a fuel for now.
17. Raw biogas contains the very contaminants that tend to damage catalysts.
2. Advanced plasma gasification works well for producing hydrogen from waste.
5. Dark fermentation followed by anaerobic digestion is a good method of producing methane and hydrogen.
26. There is not the energy payback to justify producing hydrogen.
Theme 5: Risk and public acceptability
27. There is risk involved in any technology.
16. Producing hydrogen locally can overcome negative perceptions of hydrogen.
23. The public do not understand the concept of making hydrogen from waste.
24. Environmental, social and economical impacts must be considered when making decisions about hydrogen.
30. Waste and energy professionals do not share a common language.
7. Face-to-face communication is best for hydrogen.
8. Fukushima has shown how explosive hydrogen can be.

4.2 Q methodology surveys

All twenty-five Q methodology surveys were conducted face-to-face and digitally recorded. This created a wealth of qualitative data from a diverse group of expert participants (Table 4.2 describes their occupations). Each participant was asked to fill out the survey and the raw data were recorded, as described in section 3.3.1. Figure 4.1 shows how the raw data were collected and recorded at the time of survey.

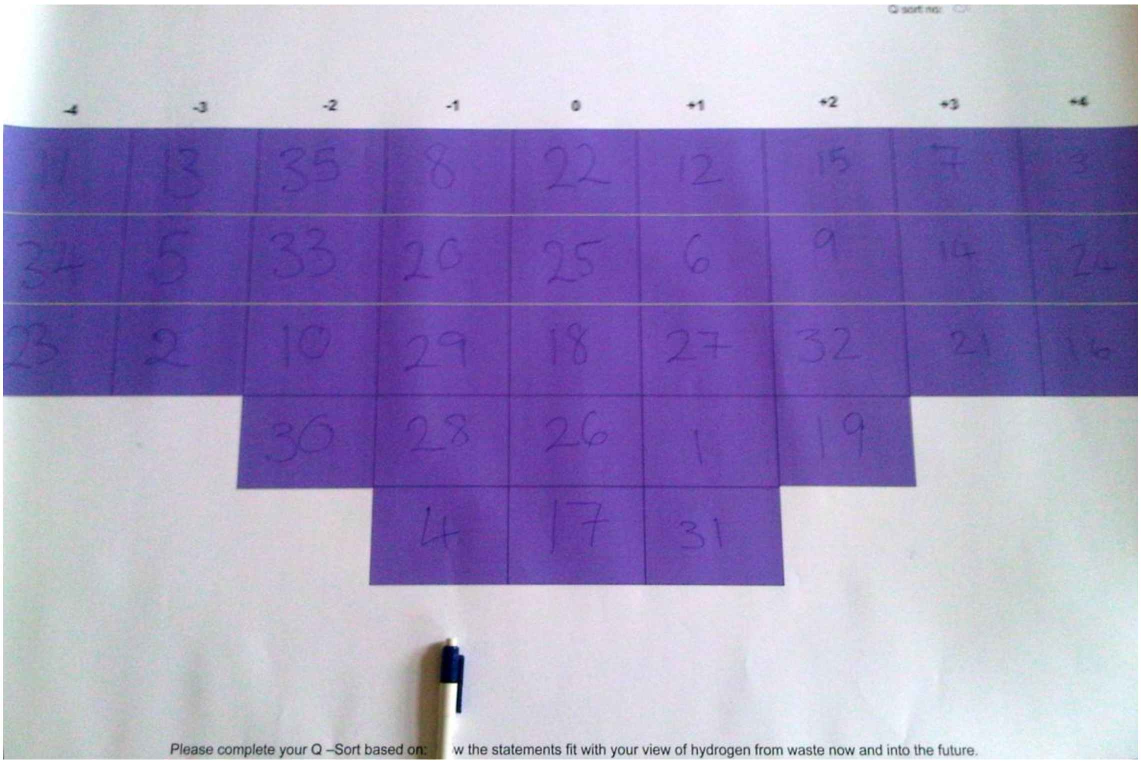


Figure 4.1. The raw data recorded by hand onto the Q sort sheet following the Q sort.

4.3 Factor Results using PCQMethod software

Nine factors were produced from the analysis of the recorded data using PCQMethod. Figure 4.2 shows the significance levels of all the Q-sorts for each factor. The significance level indicates which factor each sort is most closely related to and is produced during the software analysis. For a Q-sort to be significant for a factor it has to reach a significance level which is unique to each Q methodology survey conducted. In this case, the significance level is 44 or above (denoted in Figure 4.2 by an asterisk). The sorts that meet or exceed the significance level all have an association with one of the factors (PCQ 2012). Many of the sorts will have an association with more than one factor. However, if the significance level is below 44, then the views and perspectives of that participant are not close enough to that factor to make a clear association.

From these nine factors, three distinct factor identities were revealed. These were Factors one, two and six, shown in Figure 4.2. The factors were chosen based on the numbers of Q sorts weighting on that factor and the distinctiveness of the statements involved in those Q sorts. For example, as shown in Table 4.1 below, the two factors with the largest number of sorts weighting on them were Factors 1 and 2. Only two further factors, 6 and 8, had more than two Q sorts weighting on them. Both were analysed, but, because factor 8 did not produce an identity distinctly different to the others, the sorts weighted here could be considered to fit into the three identities constructed from factors 1, 2 and 6.

Varimax Rotation

Sort	Label	Factors 1	2	3	4	5	6	7	8	9	h2
1	01	17	16	19	15	-63*	-3	4	7	2	52
2	02	53*	-19	-5	8	-26	7	38	8	-21	61
3	03	65*	-4	16	-5	-25	12	25	18	5	63
4	04	32	-21	-7	22	-17	57*	6	21	-9	62
5	05	44*	-13	-1	-10	-52*	35	3	3	-26	70
6	06	46*	-13	-2	-11	-33	24	58*	-1	16	79
7	07	38	-41	-15	-23	-40	9	19	-3	10	62
8	08	26	-21	9	-12	0	27	19	68*	-10	73
9	09	53*	-32	-9	6	-15	37	3	0	14	58
10	10	36	-77*	2	-14	1	7	1	18	3	79
11	11	29	-8	1	24	0	5	63*	21	-2	61
12	12	27	-18	60*	-23	-8	18	21	-12	-12	64
13	13	19	-21	-2	-10	0	76*	4	5	5	68
14	14	64*	-20	3	0	-12	25	8	20	-19	63
15	15	34	-47*	7	0	-4	11	33	23	-29	61
16	16	32	3	11	-14	9	57*	42	3	-18	69
17	17	0	-3	50*	6	-5	-6	-5	-6	2	27
18	18	-2	-66*	2	-6	-1	31	-16	44*	-10	78
19	19	5	-50*	39	21	1	9	7	19	30	60
20	20	22	-59*	6	-10	-26	37	25	9	7	71
21	21	9	-71*	18	-29	21	7	11	-16	-12	74
22	22	7	-4	-15	-4	-5	0	5	56*	4	36
23	23	10	-35	0	-59*	1	36	9	24	8	70
24	24	76*	-12	15	-4	-2	19	21	5	5	72
25	25	0	-9	-3	-73*	4	-4	-12	6	-3	56

* Denote a loading significant at 44

Factors	1	2	3	4	5	6	7	8	9	Totals
eigens	3.43	3.15	1.00	1.40	1.30	2.23	1.59	1.43	0.52	16.04
% variance	14	13	4	6	5	9	6	6	2	65

Figure 4.2. Significance loading on centroid factors following varimax rotation.

Factors 1 and 2 were developed from the largest number of individuals meeting the significance level loading on that factor. Although Factor 6 had a smaller number of individuals significantly loading on it, it emerged as a distinctly different factor. One participant did not load significantly on any factor and the remaining factors (6) did not have enough participants loading on them to develop an identity that was significantly different to the three identified.

From these results the Q-sorts were grouped with their associated factor and the weighting on the statements examined. Table 4.2 shows where, within the nine factors produced, each participant's Q methodology survey fell.

Table 4.2. Participants' stated occupation

Factor	Sort	Participant's profession
1	02	Electro chemist
	03	Electro chemist
	05	Catalyst Chemist
	06	Hydrogen technologist
	09	Chemical engineer
	14	Hydrogen technologies
	24	Energy consultant
2	10	Waste expert
	15	Waste expert
	18	Chemist membranes
	19	Sustainable development expert
	21	Energy policy maker
3	12	Energy policy
	17	Waste policy
4	23	Bioenergy consultant
	25	Energy consultant
5	01	Hydrogen futures
	05	Chemist catalyst
6	04	Chemist catalysts
	13	Automotive industry
	16	Waste expert
7	06	Hydrogen technologist
	11	Energy professional
8	08	Waste regulator
	18	Chemist membranes
	22	Hydrogen economy advocate
9	0	

The statements from factors 1, 2 and 6 were analysed further to establish the detail of the identities.

4.3.1 Factor 1 – Hydrogen from Waste Advocates

Five sorts showed significance for Factor 1 - "Hydrogen from waste advocates". The weightings for each statement are shown in Table 4.3, with the statements listed in Table 4.4. While weightings -1 and +1 are not shown because they represent no significant feeling or perception and are not included in the makeup of the factor, the neutral point is included to show where the participant feels least confident about making a decision.

The statements which appear most frequently in each column are identified as the mode values and are highlighted in Table 4.3. Using the modes, a picture of the factor identity can be developed. As an example, statement 6 (Energy from waste should be a point of last resort) is ranked at -4 by all respondents loading on this factor, showing that all the respondents strongly disagree with it. Eighteen statements make up this factor.

Table 4.3. Statement weightings for Factor 1.

Sort	Ranking						
	-4	-3	-2	0	2	3	4
02	6 10 15	8 11 13	26 29 33 35	2 9 14 20 27	4 5 12 17	24 30 32	18 21 31
03	6 13 20	8 11 35	10 26 32 33	1 3 5 23 25	7 21 29 34	14 22 31	18 19 24
05	6 26 30	8 13 33	10 11 34 35	2 7 9 22 29	4 5 17 24	1 14 31	12 25 27
06	6 13 26	10 20 35	1 9 11 30	4 8 12 16 22	19 23 24 28	27 31 32	5 18 21
09	6 25 32	10 26 33	15 18 20 35	2 3 7 23 34	1 5 16 24	4 28 29	17 27 31

Table 4.4. Statements making up Factor 1, from positive to negative.

No:	Statement
Feel most strongly about/ agree with most	
21.	The inhabitants of a village or town can directly benefit from making fuel from their waste
27.	There is risk involved in any technology
32.	We have a gas grid we could use for hydrogen.
31.	Waste is a great potential energy source
24.	Environmental, social and economic impacts must be considered when making decisions about hydrogen.
17.	Raw biogas contains the very contaminants that tend to damage catalysts.
5.	Dark fermentation followed by anaerobic digestion is a good method of producing hydrogen.
Neutral Statements	
23.	*The public do not understand the concept of making hydrogen from waste.*
22.	*The input and resources put into creating networks is greater than the economic output.*
7.	*Face-to-face communication is best for hydrogen.*
2.	*Advanced plasma gasification works well for producing hydrogen from waste.*
Feel least strongly about/ agree with least.	
35.	Currently renewables are locked out of the energy system.
15.	If energy from waste is taken to a point that it is so efficient it will deincentivise reducing and recycling materials.
11.	Hydrogen use for fuel is not yet close to market development.
33.	Without incentives hydrogen production plants will never get built.
26.	There is not the energy payback to justify producing hydrogen.
13.	Hydrogen will have no role in a future energy system.
6.	Energy from waste should be a point of last resort.

4.3.1.1 Construction of Factor 1

Respondents classified in Factor 1 appear to actively advocate and think positively about hydrogen from waste and other energy from waste technologies. The demographic of this factor is predominately chemists working on new technologies to produce hydrogen and hydrogen technology experts. Factor 1 respondents responded most strongly about statement 21: that the inhabitants of a town or village can directly benefit from making fuel from their waste. These benefits can be interpreted as sustainable development benefits or community action benefits. The respondents are advocates of new and emerging technologies, such as dark fermentation, and they promote combining new technologies with old, for example using the existing gas grid for transporting hydrogen as a fuel. From the opinions and drivers articulated during the Q sorts, sustainability and considerations of environmental impacts are high on their agenda. They are aware of the difficulties of producing hydrogen from waste and strongly agree with statement 17: Raw biogas contains the very contaminants that tend to damage catalysts. From these results, it can be said that the respondents in Factor 1 have a good understanding of the technologies involved in the production of hydrogen from waste, particularly in the case of waste biogas and syngas.

Those associated with this Factor believe strongly that producing energy from waste will not impact on the recycling system and will contribute to more sustainable energy sources. They are confident that hydrogen will play a significant role in the future and that it is ready for use today, the advocates also believe that renewable energy technologies are not 'locked out' of the current UK energy system.

Although the advocates thought and spoke positively about the production of hydrogen from waste during the Q sort process, this group do not feel confident that they understand how the public perceive this. They see issues surrounding the sustainable production of hydrogen from waste and are unsure of the best route to communicate the possibilities that hydrogen production from waste can offer the public.

4.3.2 Factor 2 – Cautionary Environmentalists

The same process as described in Factor 1 to identify the mode statements was carried out to analyse Factors 2 and 6. Table 4.5 shows the weighting of the Q sort statements for Factor 2.

Table 4.5. Statement weightings for Factor 2.

Sort	-4	-3	-2	0	2	3	4
10	8 18 33	6 7 15	2 3 13 32	5 11 12 20 33	4 17 19 23	22 28 34	24 27 31
15	6 8 13	7 23 35	1 11 15 35	2 3 5 17 32	4 21 26 28	12 18 31	24 27 34
18	8 15 18	6 26 35	1 17 13 22	2 5 14 17 20	3 25 29 31	11 24 28	10 27 33
19	2 13 32	12 16 25	8 9 18 35	5 10 11 17 20	4 6 21 33	7 30 34	24 27 28
21	8 22 35	3 9 13	7 20 26 33	1 6 12 17 23	11 14 29 30	16 19 31	24 27 28

Table 4.6 identifies the statements that make up Factor 2 – "Cautionary Environmentalists".

The demographic loading on Factor 2 is more diverse than for Factor 1. The respondents include a number of policy makers in the fields of waste, sustainable development and energy and also those working as chemists in academia. From this, it seems that the opinions and perspectives given to create this factor are not wholly based on an individual's occupation and that being associated with this factor is not simply a consequence of a respondent's profession. Nevertheless, it is likely that the respondents' backgrounds and professional activities influenced their choices for weighting the statements.

Table 4.6. Statements making up Factor 2, from positive to negative

No:	Statement
Feel most strongly about/ agree with most	
27.	There is risk involved in any technology.
24.	Environmental, social and economic impacts must be considered when making decisions about hydrogen.
34.	If there were real impetus from the automotive industry, the production of hydrogen would happen more quickly.
28.	There must be a market to produce hydrogen.
31.	Waste is a great potential energy source.
29.	The UK must keep pace with hydrogen developments in Germany, Japan and the US.
21.	The inhabitants of a village or town can directly benefit from making fuel from their waste.
4.	Companies must see hydrogen as a credible market
Neutral Statements	
20.	*The economics do not exist to justify hydrogen from waste.*
17.	*Raw biogas contains the very contaminants that tend to damage catalysts.*
5.	*Dark fermentation followed by anaerobic digestion is a good method of producing methane and hydrogen*
Feel least strongly about/ agree with least.	
1.	10% of world energy might come from waste.
35.	Currently renewables are 'locked out' of the energy system.
6.	Energy from waste should be a point of last resort.
7.	Face to face communication is best for hydrogen.
13.	Hydrogen will have no role in a future energy system.
18.	The bureaucracy in the UK government system is a huge barrier to emerging technologies
8.	Fukishima has shown how explosive hydrogen can be.

4.3.2.1 Construction of Factor 2

Respondents classified in Factor 2 advocate changes that bring environmental and societal benefits. From the digital recordings of the Q sorts, it was evident that respondents weighting on this factor consider sustainable development to be at the heart of their activities and opinions. They believe strongly that all technologies pose a risk and that hydrogen producing technologies are no different. Although they accept that hydrogen will have a role in a future energy system, they are not clear as to the size of this role. They do not believe that hydrogen should be produced unless there is a market for it and that companies (especially those in the automotive industry) must buy into the idea of hydrogen as a future energy source, if its development is to be accelerated. This is coupled with a view that the UK should be aware of what is happening in countries that are leading the transition to hydrogen. The respondents do not express views on how they see hydrogen being produced, but they believe strongly that the inhabitants of a town or village can directly benefit from making fuel from their waste (statement 21).

The Cautionary Environmentalists are thus keen for waste to be used as a fuel to create energy and they do not believe that renewable energy technologies are locked out of the current UK energy system. This group, although strongly influenced by the impact of technologies on the environment and society, are not put off the idea of hydrogen as a fuel despite large industrial accidents, and do not believe that the government bureaucracy is stifling change.

Although this group actively promotes change, they know little of the technologies that can be utilised to bring about these changes and are not confident as to whether the production of hydrogen from waste is economically viable. This is why they have been labelled 'Cautious Environmentalists'.

4.3.3 Factor 6 – Hydrogen Technologists

In this factor, while many of the sorts loaded on it, only three sorts met the significance criterion of 44. This sort was explored to establish if a significantly different perspective from Factors 1 and 2 could be developed. The demographic of this factor includes: a chemist (catalysts), an automotive industry professional and a waste expert. The term "Hydrogen Technologists" was used to describe this group, as each individual in this Factor identity was either working in the development of hydrogen technologies, primarily for automotive, or in waste technologies to manage waste gas. All participants described a strong technology influence in their interviews and this is reflected in the title of this Factor.

Table 4.7 shows the weightings of the statements provided by the participants who are most closely aligned with Factor 6.

Table 4.7. Statement weighting for Factor 6.

Sort	-4	-3	-2	0	2	3	4
04	6 10 15	8 20 26	13 18 19 22	7 9 23 25 27	1 3 11 33	12 14 16	24 29 31
13	6 13 32	9 20 22	1 7 18 35	2 17 24 27 33	3 8 16 23	5 28 31	12 14 29
16	13 20 35	10 22 26	7 15 17 25	3 8 11 27 33	4 21 31 34	1 5 23	2 12 18

Statements that provide the detail for the identity revealed by Factor 6 are shown in Table 4.8.

Table 4.8. Statement making up Factor 6, from positive to negative.

No:	Statement
Feel most strongly about/ agree with most	
12.	Hydrogen will have a large role in a future energy system.
29.	UK must keep pace with developments in Germany, Japan and the US.
5.	Dark fermentation followed by anaerobic digestion is a good method of producing methane and hydrogen
3.	An innovation system around hydrogen from waste needs to be developed to keep hydrogen on the table.
27.	There is risk involved in any technology.
33.	Without incentives hydrogen production plants will never get built.
18.	The bureaucracy in the UK government system is a huge barrier to emerging technologies
Neutral Statements	
7.	*Face to face communication is best for hydrogen.*
Feel least strongly about/ agree with least.	
20.	The economics do not exist to justify hydrogen from waste.
22.	The input and resources put into creating networks is greater than the economic output.
26.	There is not the energy payback to justify producing hydrogen.
13.	Hydrogen will have no role in a future energy system.
6.	Energy from waste should be a point of last resort.

4.3.3.1 Construction of Factor 6

Factor 6 respondents feel strongly about the creation and development of new technologies. This group believes strongly that hydrogen will have a large role to play in the future as a fuel and energy provider. The Hydrogen Technologists believe that the UK must keep up with other leading countries in the transition to a hydrogen economy, and that there are good emerging technologies that can assist with the transition. This group shows that they are aware of the risk involved in all technologies and believe that in the UK some assistance with developing hydrogen plants and establishing an innovation system for the creation of hydrogen from waste are both important elements in moving forward.

These experts do not agree with the statements that the economics are not in place to justify the creation of hydrogen from waste and that there is insufficient energy payback. They advocate the use of innovation systems to promote the development of new technologies for hydrogen production from waste, but are unsure of the best type of communication media to use.

During the interviews, respondents in this factor did not consider the sustainability of the process as a priority. They agreed strongly with statement 12: hydrogen will have a large role in a future energy system and statement 29: the UK must keep pace with developments in Germany, Japan and the US. It could be understood from this that the focus for respondents in the Hydrogen Technologist's group is on developing the technologies and moving them towards commercialisation.

4.4 Consideration of factor identities: Discussion and emerging themes

In this section, the factor identities are discussed and some key themes are identified.

4.4.1 Discussion of the construction of factor identities

The three factors uncovered by the analysis of the Q-sorts and their similarities, differences and relationships are now discussed in more depth.

The concept of creating hydrogen from waste was received positively by all three factor identities. The respondents loading with the significance level on these factors clearly identified the need to consider the role of hydrogen in meeting the UK's future energy needs. The respondents provided a clear vision: that taking advantage of advancing technologies to reduce emissions to land, air and water whilst reducing the impact of waste disposal was a sensible approach. From the Q sort factor identities, the hydrogen technologists were less concerned about sustainable development than the hydrogen from waste advocates and cautionary environmentalists.

Managing resources locally was important to the Hydrogen from Waste Advocates and the Cautionary Environmentalists. Respondents loading with the significance level on all three factors agreed that anaerobic digestion had potential for producing hydrogen from waste as a renewable resource. This is consistent with literature describing the importance of hydrogen as a future solution to environmental and transport problems (Balat 2008; Balat and Kirtay 2010). The types of waste that could be utilised in this process include: waste food, waste biomass, farm wastes and wastewater.

Elements of risk acceptance were reflected in statement 27 there is risk involved in any technology, which featured in all three factors. The Hydrogen from Waste Advocates and Hydrogen Technologists accepted that such risk was part of the transition process and were of the view that the risks associated with all technologies would not outweigh the benefits of advances in hydrogen production technologies. However, the Cautionary Environmentalists showed a more prudent approach. Respondents most closely associated with this group weighted levels of risk and following technology advancements in countries like the USA, Japan and Germany similarly. In these countries, the hydrogen production and use agenda is more developed than in the UK. These respondents demonstrated a need to feel confident about the capabilities of technologies being developed in other countries, before committing to similar technologies in the UK.

4.4.2 Discussion of results, with particular reference to technological innovation systems

The Hydrogen from Waste Advocates (Factor 6) and Hydrogen Technologists (Factor 1) revealed a more conventional approach towards an innovation system compared to the cautionary environmentalists. They voiced strong concerns around statement 27: there is risk involved in any technology. In addition their strong agreement with statement 28 there must be a market for hydrogen could be interpreted as wanting to see the build-up around the technological innovation system. This could give these respondents confidence about statement 20: the economics do not exist to justify hydrogen from waste, and statement 23: the public do not understand the concept of making hydrogen from waste. It could also be argued that, as the different groups of respondents in the Hydrogen from Waste Advocates and Cautionary Environmentalists gain confidence in different elements of the technological innovation system, they may begin to better understand their own role and that of others in the system. This could in turn lead to more successful partnerships.

Only respondents in the Hydrogen Technologists' factor felt that it was necessary to develop a specific innovation system, as demonstrated by their loading on statement 3: an innovation system around hydrogen from waste needs to be developed to keep hydrogen on the table. This was weighted at +2, indicating that it is not a particular concern for these respondents. Hydrogen from Waste Advocates and Hydrogen Technologists agreed that bureaucracy in the UK was a significant barrier to advancing hydrogen from waste technologies. Hydrogen from Waste Advocates did not believe that incentives would be required to aid the development of hydrogen, whereas Hydrogen Technologists strongly agreed with statement 33: Without incentives hydrogen production plants will never get built.

In their paper on the build-up of a technological innovation system for hydrogen and fuel cell technologies, Suurs *et al*. (2009) provide the following example of why incentives are important;

> "…firms looking to exploit the benefits of fuel cell technologies will need to co-operate with other firms and research institutes in order to develop a product. In addition they require support from governments, e.g. subsidies or other stimuli. Governments in return require a legitimate reason for spending public money…" (Suurs *et al.* 2009 pg: 9640)

Divergence in opinion between Hydrogen from Waste Advocates and Hydrogen Technologists regarding the barriers to technological development could mean that they are working towards achieving different outcomes from their research and development activities. The Hydrogen from Waste Advocates group has a demographic that is predominantly represented by academia, whereas the Hydrogen Technologists group is represented by the fuel cell and waste industry. Both of these groups require an input from each other to develop, diffuse and utilise a new technology. Hydrogen Technologists will be driven to find investment from another party in an attempt to progress the transition to increased use of hydrogen technologies. This is not necessarily the case for representatives of the Hydrogen from Waste Advocates, who may look for investment from companies interested in taking up the new technology. This in turn could cause a conflict between the two groups should they be involved in projects together. The Hydrogen Technologist seeks investment to begin the development of a new technology and the Hydrogen from Waste Advocate wishes to focus on the development of an existing technology. The idea would then be to later sell it to an end-user who will make investment at a later date. Both of these groups will require input from the policy makers and regulators who make up the majority of Factor 2 respondents, characterised as Cautionary Environmentalists.

The approach revealed by the Cautionary Environmentalists could cause difficulties in developing a successful innovation system around the sustainable production of hydrogen from waste. To achieve the support and incentives from governments and regulators that Factors 1 and 6 require to work successfully together, the Factor 2 group needs to be convinced that the proposals for new technologies and possible infrastructure investment are sound and 'low risk'. As noted, Factor 2 consists of cautionary environmentalists who weighted heavily on statements relating to sustainable development and the risk that new technologies may give rise to. This group has a role in terms of the different functions identified within the innovation system (Bergek *et al.* 2008):

- Knowledge development and diffusion
- Influence on the direction of search
- Entrepreneurial experimentation
- Market formation
- Legitimation
- Resource mobilisation
- Development of positive externalities

This cautionary approach across all functions could cause prolonged delays and require the provision of substantial evidence for members of this group to support any particular technology direction. The Cautionary Environmentalist may appear to be unreasonable to other members of the technological innovation system by requesting 'unreasonable' amounts of evidence to gain their support for a technology. The need for this evidence may be because, in the case of emerging technologies and systems, there will be an element of risk in supporting a new technology. Hydrogen from Waste Advocates and Hydrogen Technologists may not yet have the evidence the Cautionary Environmentalists desire. This evidence will most likely be gathered from exercises that take place in the innovation system around research and pilot programmes.

The factors also reveal, however, that the Hydrogen from Waste advocates share some of the concerns of the Cautionary Environmentalists. For example, the Hydrogen from Waste advocates strongly agree with statements 27 (there is risk in any technology) and 24 (Environmental, social and economic impacts must be considered when making decisions about hydrogen). This may mean that they too would like further assurances of the safety and efficiency of new technologies before advocating their use with wastes.

Cautionary Environmentalists may also be influenced by wider societal and political cycles. This means that the guidance given to Hydrogen from Waste Advocates and Cautionary Environmentalists from Hydrogen Technologists on the likely technologies that they may support could be insufficiently clear, and subsequently impact on the nature of investments that may then follow. The result of this could be limited positive feedback loops within the technological innovation system, preventing success across the functions.

As previously described, the innovation system is non-linear, such that the functions influence each other and the success of one function can depend on the success of another (Hekkert *et al.* 2007). The networks of information, knowledge and success run throughout the innovation system. Stifled communication or a lack of understanding of the best medium for communicating with actors and institutions influencing the functions will cause significant damage to the success of the innovation system.

The Q methodology results show that all three Factor identities were unsure of the most effective way to communicate their research results and development activities to other innovation system stakeholders or to the wider public. In particular, the respondents were not sure of the best media for communicating their requirements and outputs. Many of the respondents were concerned that the economic return of knowledge sharing networks may be less than the cost of running the network; this could be a factor in either not developing or supporting these knowledge networks. Communication was an area where all respondents did not seem clear on the best approach or how effective different types of communication may be.

4.4.3 Concluding comments

The respondents have provided significant insights into why the technologies available to produce hydrogen from waste sustainably have not yet been successfully commercialised in the UK. The data obtained suggest that in order to improve the success of the TIS, improvements in the innovation relationships and networks would need to be made.

These data suggest that the considered role of the Cautionary Environmentalists is creating a barrier to commercialisation of new technologies by their reluctance to accept the risks of these technologies or to support a particular technology path. This is reflected in the evidence that the majority of pilot projects remain in academic institutions. This is an issue which would need to be addressed to enable support in the TIS more consistently and across all functions, if significant progress is to be made in the near future with hydrogen from waste. These concerns may be addressed through the communication of successful demonstration and laboratory pilot programmes where risks had been shown to be decreasing. It could be argued that there is a need to develop appropriate skills to manage the communication of successful innovation, in order to alleviate the misunderstandings of this part of the innovation system around hydrogen production from waste.

4.5 Contribution to achieving aims and objectives

The main research question presented initially in Chapter 1 asks: *Does a conceptual model of the technological innovation system for hydrogen production from waste accurately reflect "real life situations"?*

The results of the Q methodology activities presented in this chapter begin to answer this question. The results have provided insights into the perspectives of experts involved in the emerging TIS for hydrogen production from waste. These experts are operating in "real life situations" where the actions, decisions and perceptions of each other provide the boundaries of the relationships developed in the TIS. The results from this Q methodology do reflect the way 'real' experts think about the hydrogen from waste issue. As such, the different discourses emerging from each of the factor identities have been used to inform the development of relationships between functions of innovation in the Interaction Matrix-Technological Innovation Systems model presented in Chapter 5.

More specifically, Q methodology has allowed for the characterisation of experts who work in the technological field. This contributes to meeting the requirements of Objective 2: *To characterise, using Q methodology, the different expert communities involved in the production of H_2 from waste in the UK and their role in the technological innovation system.*

In order to create a model built up from the functions of innovation presented by Bergek *et al.* (2008) and described in Chapter 3, the perspectives of the experts involved in the innovation system must be reflected. The results of the Q methodology surveys are considered and incorporated in the development of the forty-two matrix relationships for the IM-TIS model.

4.5.1 Study limitations

It is important to acknowledge the limitations of this approach, as well as its strengths. Firstly, this study was undertaken between March and May 2012 and therefore represents a snapshot in time. It should not be assumed that the three Factors produced are fixed points of view. The perspectives are based on each respondent's knowledge of the key themes presented in the Q methodology survey at that time. Secondly, the Q methodology does not allow for further interpretation to establish whether the perspectives uncovered would be representative of the sector across the country. The results are only representative of the twenty-five experts in the study group. Thirdly, the Factors revealed cannot be used to represent any level of knowledge or understanding of any groups who are non-experts or work outside the field of the sustainable production of hydrogen from waste as described in the demographics.

4.6 Concluding Comments

The application of the Q methodology to this subject area enabled more detailed reflection of the development of the emerging innovation systems in the three regional case study areas as is presented later in Chapter 6. This will include the different barriers and strengths that the factor identities bring to the system and their relationships with each other. The role of the individual in the innovation system may prove crucial in new and emerging TIS, as the expert may represent the view of the actors and institutions that provide the architecture of the TIS. It is important to note that, as stated above, it is not possible to say that the results of the Q methodology are a reflection of all actors involved in the production of hydrogen from waste. However, the results can be used to further inform the development of a technological innovation system for hydrogen from waste in the UK.

This Chapter is followed by the development of the new IM-TIS model, an amalgamation of the Rock Engineering Systems model and the functions of innovation framework. The results of the case study analysis using this model are given in Chapter 6.

4.7 References

Balat M., Potential importance of hydrogen as a future solution to environmental and transportation problems. International Journal of Hydrogen Energy 33 (2008) 4013-4029

Balat H., Kirtay E. Hydrogen from biomass – Present scenario and future prospects. International Journal of Hydrogen Energy 35 (2010) 7416-7426

Bergek A., Jacobsson S., Carlsson B., Lindmark S., Rickne A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (2008) 407-429

Hekkert M.P., Suurs R.A.A., Negro S.O., Kuhlman S., Smits R.E.H.M., Functions of innovation systems: a new approach for analysing technological change. Technological Forecasting and Social Change 74 (2007)

Suurs R.A.A., Hekkert M.P., Smits R.E.H.M. Understanding the build up of a technological innovation around hydrogen and fuel cell technologies. International Journal of Hydrogen Energy 34 (2009) 9639-9654

PCQ Users Guide. Analysis Software for Q Technique. Version 1.4.1 2001

Van Excel N.J.A., de Graff G. Q methodology: A sneak preview. Erasmus MC, Institute for Medical Technology Assessment. Rotterdam. (2005)

Venables D., Pidgeon N., Simmons P., Henwood K., Parkhill K. Living with Nuclear Power: A Q-Method Study of Local Community Perceptions. Risk Analysis 29, No. 8, (2009) 1089-1103

5. Development of the Interaction Matrix - Technological Innovation Systems (IM-TIS) model

This chapter will describe the Rock Engineering Systems (RES) methodology developed by Harrison and Hudson (2006) and its adaptation to develop an idealised technological innovation system. This adaptation incorporates the functions of the innovation approach developed by Bergek *et al.* (2008). IM-TIS operates through an interaction matrix and presents a new model. The model is called the 'Interaction Matrix–Technological Innovation System' (IM-TIS). The IM-TIS Model was developed as part of this research and was designed to analyse the innovation system supporting sustainable production of hydrogen in three case study regions: London, Tees Valley and South Wales.

The Chapter has the following structure: in section 5.1 the development of IM-TIS is described and the relationship to the functions of innovation framework (Bergek *et al*. 2008) explained. In section 5.2, the additions to the RES model are explained, along with the model's limitations. Finally, in section 5.3, the new application of the model to explore policy pathways is presented.

5.1 Development of new technological innovation system model IM-TIS

The IM-TIS model allows for the effectiveness of the technological innovation systems within the regional case studies to be evaluated. Because the methodology identifies the system components, it is an analytical approach that studies the expected and existing workings of the emerging technological innovation system, based on the cause and effect interactions of the innovation functions within the system. The model can provide analyses of the current system and the changes required in the future to make it more effective. This type of model has not been develped or utilised before, as identified by Truffer *et al.* (2012) in their review of energy innovation systems.

The IM-TIS model offers the opportunity to examine a TIS life cycle and begin to understand the dynamics that develop and change through the maturing of a technology (Truffer *et al.* 2012). This dynamic use of the RES base model is also a new development for RES, as in the previous studies identified in Chapter 2 and 3, it has essentially only been used to examine static systems or data at a fixed point in time. During the period of this research project, it is believed that there are no known studies of RES that examine the possible changes of an engineering or biological technological innovation system over time.

The model presents the technological innovation system graphically as an interaction matrix, with the core subjects of the system presented along the principal diagonal (top left to bottom right) and the interactions between the subjects located in the off-diagonal boxes. This can be seen in Figure 5.1 below. The process then assesses the relative significance of the subjects within the system to study the interaction intensity of the technological innovation system (TIS), followed by the dominance or subordinacy of the subjects within the system. From that point, the effectiveness of each of the regional technological innovation systems can be evaluated using an index of effectiveness, through which the case studies are examined individually against the IM-TIS matrix, producing a measure of percentage effectiveness for each case study.

The IM-TIS model was developed in the process of this research to provide a new way of examining technological innovation systems in case study regions. The results of the application of the model to these case studies are given in the following Chapter (6). In addition to this, the model was further used to identify policy pathways for the possible implementation of policies relating to the production of hydrogen from waste. It is possible from the results of the application of IM-TIS to determine over time which interactions based on the subjects of the TIS should occur first so that the case study TIS can move towards a system where all interactions exist.

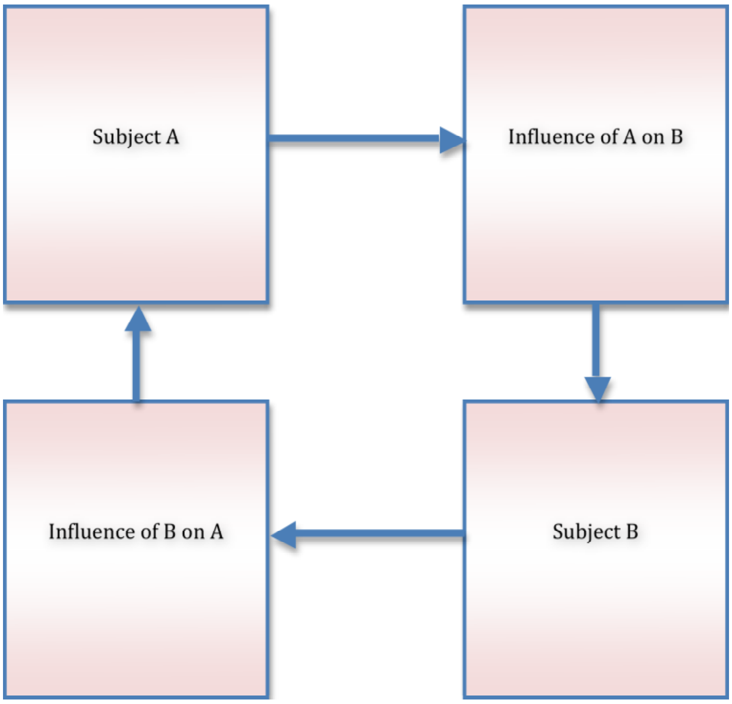


Figure 5.1 Principle of the RES interaction matrix (Harrison and Hudson 2006).

Figure 5.1 shows the matrix in its simplest state with only two subjects (components). These subjects represent the functions of innovation and the influence boxes show how each function impacts upon the other. The 2x2 matrix is expanded to an nxn matrix (where n is the number of subjects) to include all the subjects (functions of innovation) for the case in hand and, when this is done, all of the causes and effects of the subjects upon each other can be established and considered. In this instance, the matrix presents an opportunity to identify all of the influences that all of the functions have upon each other in the idealised technological innovation system for hydrogen from waste. From these influences, it is possible to identify the effectiveness of the regional case study systems.

IM-TIS thus represents a new approach to analysing technological innovation systems by combining two existing models. In the past, the RES interaction matrix was used predominantly to address engineering and science-based problems (Hudson *et al.* 2013). The one previous application in innovation systems by Temel *et al.* (2002) was reviewed in section 3.4.1. This model differs from that of Temel *et al.* (2002) because the subjects of the matrix are taken from an existing technological innovation systems model, known as “functions of innovation” (see section 2.4.1). Temel *et al.* (2002) developed the subjects of the (Agricultural Innovation System Azerbaijan) AISA interaction matrix from their questionnaire data; whereas, in IM-TIS, the subjects are defined by the functions of innovation (Bergek *et al.* 2008).

Bergek *et al*. (2008) describe the functions of innovation model as the functional dynamics approach. This involves a seven step process that aims to be useful to innovation system researchers and policy makers by presenting a practical scheme of analysis. This scheme can be used to identify the key policy issues and set of goals in any given TIS. The main application for this stepped scheme is to assist in the identification of system failures or weaknesses. Policy makers can identify key policy challenges by using the approach of Bergek *et al.* (2008) as a focussing tool. However, the stepped approach they presented did not aim to look beyond the blocking mechanisms and policy issues that relate to the functions identified. This means that no provision for identifying and understanding the role of the relationships and interactions between the different functions or steps in the innovation system is provided and no possibilities of how a system may change with time.

Figure 5.2 below shows the abbreviated IM-TIS model and identifies how the relationships between each function may be mapped out. The relationship is shown as the influence that the first letter has on the second, for example, ‘KI’ is the influence that knowledge development and diffusion has on the influence of the direction of the search. The functions of innovation are abbreviated as follows:

K = Knowledge Development and diffusion

I = Influence on the direction of search

E = Entrepreneurial experimentation

M = Market formation

L = Legitimation

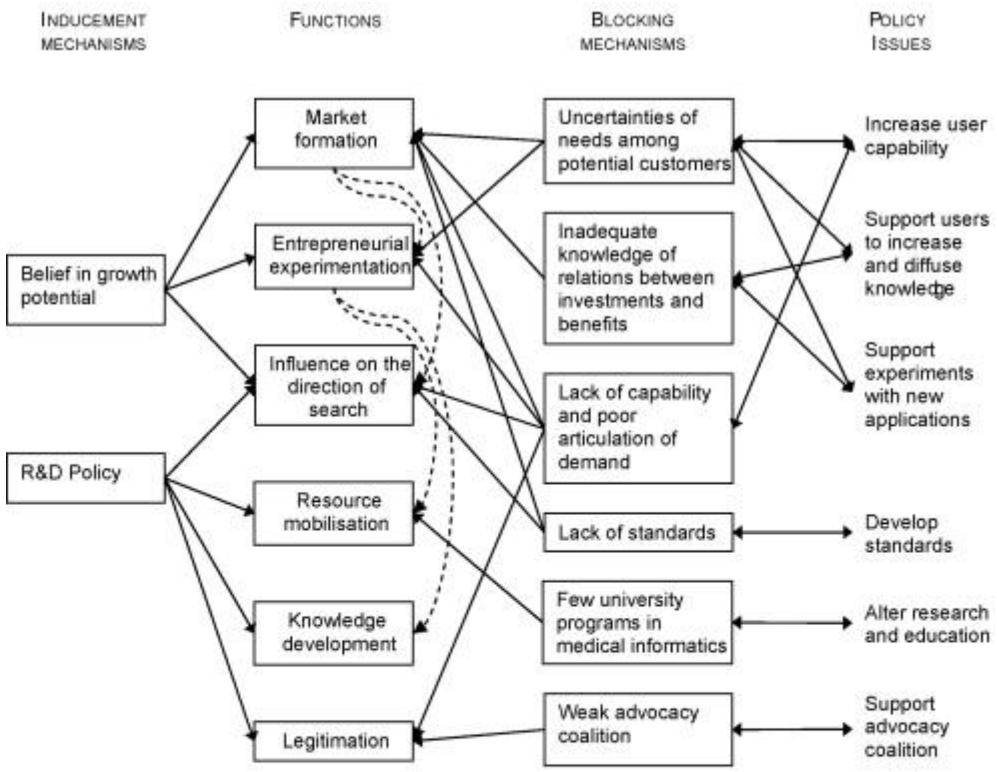
R = Resource mobilisation

D = Development of positive externalities

K	KI	KE	KM	KL	KR	KD
IK	I	IE	IM	IL	IR	ID
EK	EI	E	EM	EL	ER	ED
MK	MI	ME	M	ML	MR	MD
LK	LI	LE	LM	L	LR	LD
RK	RI	RE	RM	RL	R	RD
DK	DI	DE	DM	DL	DR	D

Figure 5.2. Abbreviated IM-TIS model showing relationships between functions.

It is argued here that, through the combination of Bergek *et al.* (2008)'s functions approach and the RES interaction matrix, these relationships can be mapped and their impact, as well as that of the functions on the system as a whole, can be better understood. In turn, this new combination of models realised in the IM-TIS offers an opportunity to map out pathways between the different functions of innovation and to identify how their interactions and relationships may affect the development of government policies relating to hydrogen production from wastes. This means that the IM-TIS model offers a chance to view a TIS over time. Furthermore, it can be adapted to suit the needs of the investigator by changing the types of relationships within the matrix itself.



<u>Figure 5.3 A visual representation of the functional approach described by Bergek *et al.* (2008).</u>

In graphical form, as seen in Figure 5.3 above, the relationships and interactions within the Bergek *et al*. (2008) framework could easily become confused and messy. The influence and relationships are not clear and connecting lines move around and between each of the functions. Figure 5.2 shows how the IM-TIS model is able to mark out clearly the influence and relationships between each function in a more structured way. All functions have a relationship with each other, but this is unclear from Figure 5.3 from Bergek *et al.* (2008).

Figure 5.3 provides the only known visual representation of an application of the Bergek *et al*. (2008)'s functions of innovation framework. Bergek *et al*. (2008) have excluded the seventh element of the functions approach ("development of positive externalities") from this diagram. The authors provide the following reasoning: that it was the view of VINNOVA (the Swedish Agency for Innovation) that this step was not required as part of the discussion around inducement, blocking mechanisms and policy issues, which were the focus of Bergek *et al.* (2008). The Figure was developed to visually display the application of the functions of innovation framework to a specific case study in Sweden of policy issues around IT in care homes. It is unknown if the absence of “development of positive externalities” would occur in all Swedish applications of the Bergek *et al.* (2008) framework. However, for the research in this thesis, this function of innovation in Bergek *et al.* (2008)’s framework is considered a critical element of the IM-TIS model and was used in its development.

In the case of IM-TIS, it is believed that the development of positive externalities shows growth within the TIS and movement further into accepted practice. Positive externalities may include new entrants into the sector, information sharing of the technologies beyond the boundaries of the TIS, and partnership developments with new organisations—which have not previously been considered to be actors within the TIS.

Table 5.1. Details of the seven functions of the innovation system, as defined by Bergek *et al*. (2008).

Function	Description
Knowledge Development and diffusion	The function captures the breadth and depth of the current knowledge base of the TIS, how that changes over time and how that knowledge is combined and diffused within the system. This function can be measured using a range of indicators including: bibliometrics, R&D projects, patents, university and professional course courses or conferences.
Influence on the direction of search	For TIS to develop there must be sufficient incentives and/or pressures for organisations to enter into it. This function is the combination of factors that cover the incentives and mechanisms for delivery that influence technologies, applications, markets, business models, etc....
Entrepreneurial experimentation	A TIS evolves under considerable uncertainty in terms of technologies, applications and markets. This function requires individuals and organisations to probe into new technologies and applications where some will fail and some will succeed. This can be measured by identifying the number of new entrants into the sector, number and types of application and the breadth of technologies used and the characteristics of complementary technologies.
Market formation	For an emerging TIS, a period of transformation may not exist, or may be greatly underdeveloped. Markets often develop in three phases: nursing, bridging and mature. These can be assessed by identifying indicators in each phase of market formation.
Legitimation	Legitimation is a matter of social acceptance and compliance with relevant institutions: a new technology needs to be considered appropriate and desirable by relevant actors in order for resources to be mobilised. New regulations, growth in the industry both show legitimation.
Resource mobilisation	As a TIS evolves, different resources need to be mobilised; these can include, finances, management, education opportunities.
Development of positive externalities	New firms entering into the emerging TIS are central to the development of positive externalities. New entrants may be in the technological field or supporting a growing supply chain. The greater the number of actors in the TIS, the greater the number of possible combinations for coalitions.

These functions of innovation are combined into the interaction matrix and act as the subjects. The interactions and relationships between them were mapped out and are presented in Figure 5.2. It is important to note that, as explained below, the interactions and relationships were developed for IM-TIS by the author of this thesis, with assistance from a colleague, to suit the requirements of this research. Of course, different researchers may find more suitable relationships for the particular TIS they are analysing. Changing the relationships does not alter the function of IM-TIS; it simply enables the model to adapt to the problem under investigation. However, it is crucial that they are kept consistent for any comparative analyses, as shown in Chapter 6.

Figure 5.4 shows the interaction matrix for the IM-TIS model with all of the cause and effect interactions that have been observed. The interactions and relationships were identified as likely interactions based on Bergek *et al*. (2008). Interactions were designed to represent likely occurrences within the technological innovation system for hydrogen from waste. These interactions included experiences and knowledge gained through the initial qualitative interview and Q methodology surveys. Note that none of the off-diagonal boxes in this matrix are empty. It can be seen in Figure 5.4 that there is a policy slant to the IM-TIS model. This is to reflect the emerging nature of the hydrogen from waste field and the potential role of the state in providing some technology ‘push’. To ensure that all interactions between the subjects of the TIS had been identified and adequately considered, they were reviewed by Nick Hacking, a member of the SUPERGEN H-Delivery Team at Cardiff University.

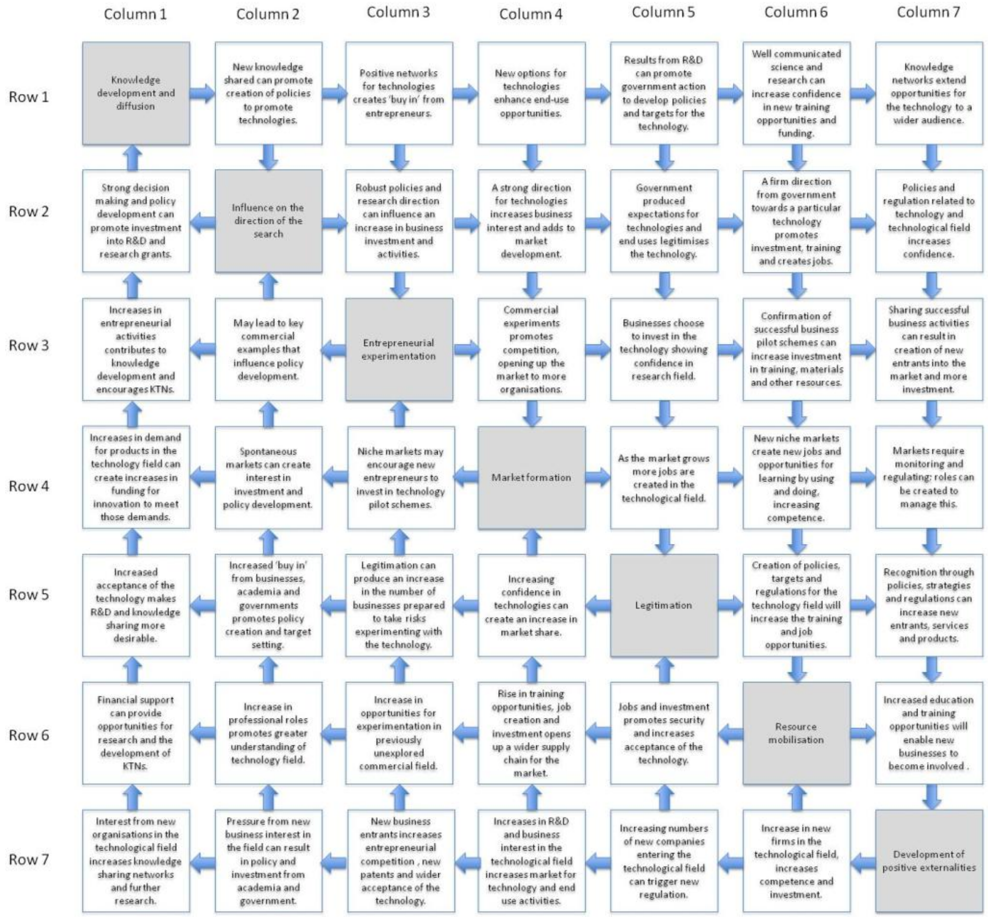


Figure 5.4. IM-TIS interaction matrix with all relationships shown.

This model, if suitably adapted, could be applied to specific case studies for any technological innovation system problem. For the hydrogen from waste case studies presented in this thesis, the case study applications of the IM-TIS models will be referred to by the following acronyms:

Original = IM-TIS

Tees Valley = H_2fW IM-TIS (TV)

London = H_2fW IM-TIS (LN)

South Wales = H_2fW IM-TIS (SW)

The subjects of the IM-TIS model are shown in grey and are the functions of innovation described in Bergek *et al.* (2008), these subjects remaiingn constant throughout all the case study investigations. However the existence and strength of the relationships and interactions, shown in white, will be under scrutiny. It will be shown that the existence or non-existence of these interactions provides the evidence for the development of the index of effectiveness and the coefficient of vulnerability for the case studies.

The next phase of the IM-TIS development is to gain understanding of the different levels of importance of each interaction within the matrix, according to a scale. The scale is based on: What level of importance do the interactions have in determining the potential effectiveness of the IM-TIS case? To address this, an Expert Semi-Quantitative (ESQ) coding system was used on a scale of 0-4 and has been allocated as shown in Table 5.2: The ESQ Level assigned to each interaction was also reviewed by Nick Hacking, a member of the SUPERGEN H-Delivery Team at Cardiff University. The importance of each interaction within IM-TIS coded by the ESQ method is, by definition, subjective, and so it is recognised that other researchers may apply different ESQ levels to each of the interactions.

Table 5.2. Expert Semi-Quantitative (ESQ) coding

Colour	Scale	Interaction
Red	0	No interaction
Purple	1	Non-critical interaction
Blue	2	An interaction that should occur regularly
Orange	3	Interactions that are general to all TIS
Green	4	Of particular importance in successful TIS

In Figure 5.4, it can be seen that there are no interactions scored as '0': to score a 0 would not be possible in a fully effective system due to the need for all interactions to occur. The majority of interactions are coded in orange at Level 3; these are interactions that would be expected in an effective TIS. Figure 5.4 shows the ESQ distribution within the IM-TIS model and illustrates that Level 3 interactions are most desirable. At Level 3 the interactions are easily achievable and show an effective system where relationships between functions are operating and the innovation system is functioning.

At Level 2, influences and relationships between functions may be weak, communication may be poor, or policy influences absent. There are many different reasons why some relationships could be considered weak. At Level 4 the interactions between functions may have a high overall impact on the whole system, but this would not be possible for all interactions. The distribution of higher ESQ levels (Levels 3 and 4) of interactions means that the TIS is able to operate efficiently. If for example, the majority of interactions were coded at Level 4, the TIS would be more susceptible to failure due to the difficulty in activating these interactions of particular importance. They are described as of particular importance due to their capability to initiate action within other interactions. If the opposite situation is described, and there are many Level 0 and Level 1 interactions, then the system is weak and may be in a failure mode or not functioning as an innovation system. A system with low Level interactions is not a system working towards achieving technological innovation and commercialisation. In this IM-TIS model, the interactions are coded in order to provide a balanced approach to technological innovation. However, the coding does show that, for an effective TIS, the majority of interactions in the matrix are interactions that should be commonplace in a functioning TIS, even one in an emergent state.

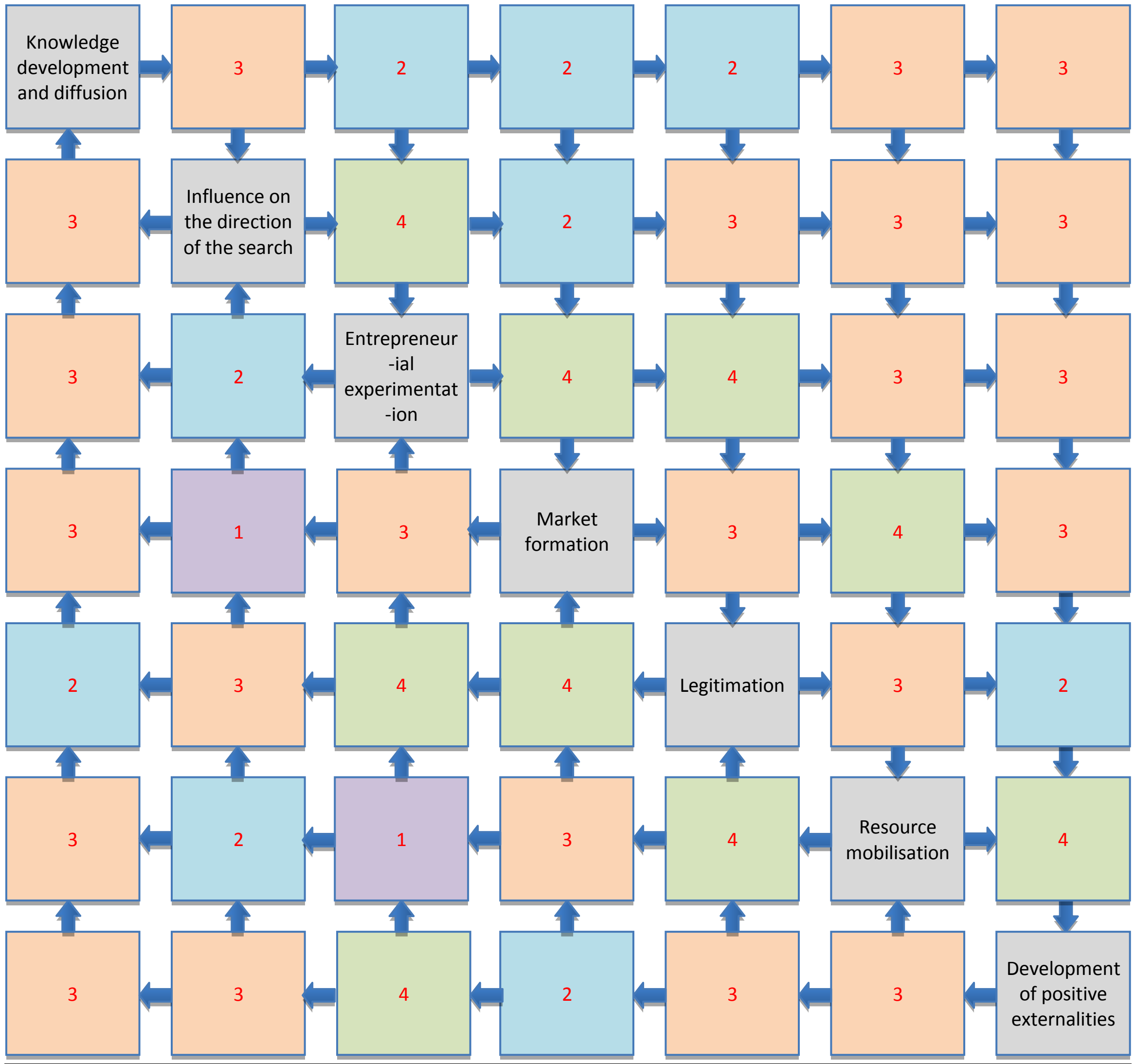


Figure 5.5. The IM-TIS with the colour coded ESQ values.

Having established the ESQ coding and distribution, the methodology then moves into the final stage of the model's development: identifying the type of system the IM-TIS is and what relationship the subjects have with each other, based on their respective causes and effects. The distribution of the ESQ coding for IM-TIS is given in Figure 5.6 below.

Referring to Figure 5.5, where the matrix has been coded using the Expert Semi Quantitative method described in Table 5.2, the cause and effect co-ordinates can be established. The total of the values in the cells in a row is termed the 'cause', based on the way in which the subject in a leading diagonal box (see the shaded boxes in Figure 3.4) influences the system. Similarly, the sum of the values in a column through a leading diagonal box is termed the 'Effect', due to the influences of all the other subjects in the system on the it.

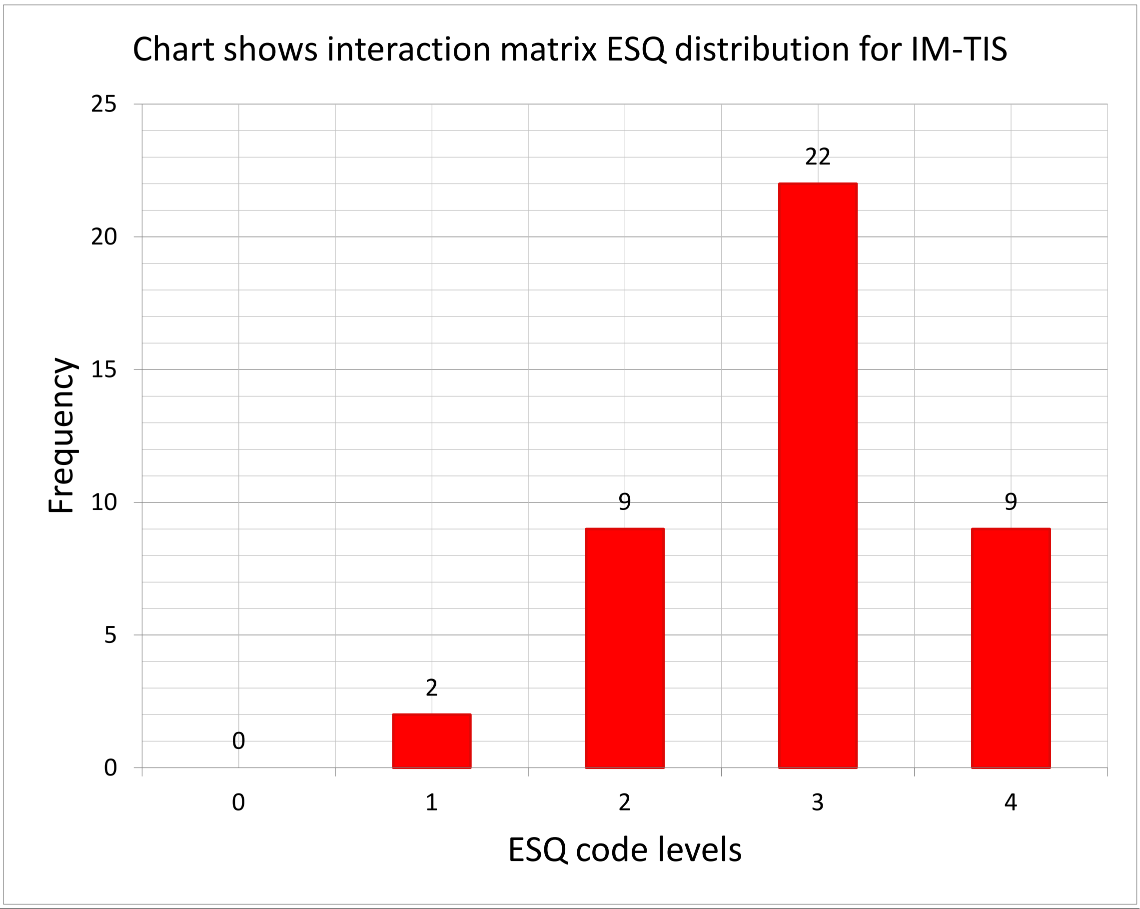


Figure 5.6. ESQ distribution graph for IM-TIS.

This process allows us to find the Cause-Effect (C–E) co-ordinates. For the_first function shown in Table 5.3 below (Knowledge development and diffusion), the C–E co-ordinates are (15,17), i.e., the totals of Row 1 and Column 1 respectively. Undertaking the same operation for the other six subjects provides the C-E co-ordinates for all the subjects.

Table 5.3. Cause-Effect Co-ordinates for IM-TIS.

Subjects (Functions of Innovation)	C-E Co-ordinates
1. Knowledge development and diffusion	(15,17)
2. Influence on the direction of the search	(18,14)
3. Entrepreneurial Experimentation	(19,19)
4. Market Formation	(17,17)
5. Legitimation	(18,19)
6. Resource Mobilisation	(17,19)
7. Development of positive externalities	(18,18)

These co-ordinates are then plotted onto a cause-effect graph, to show what type of system the IM-TIS model represents; this is shown in Figure 5.7 below.

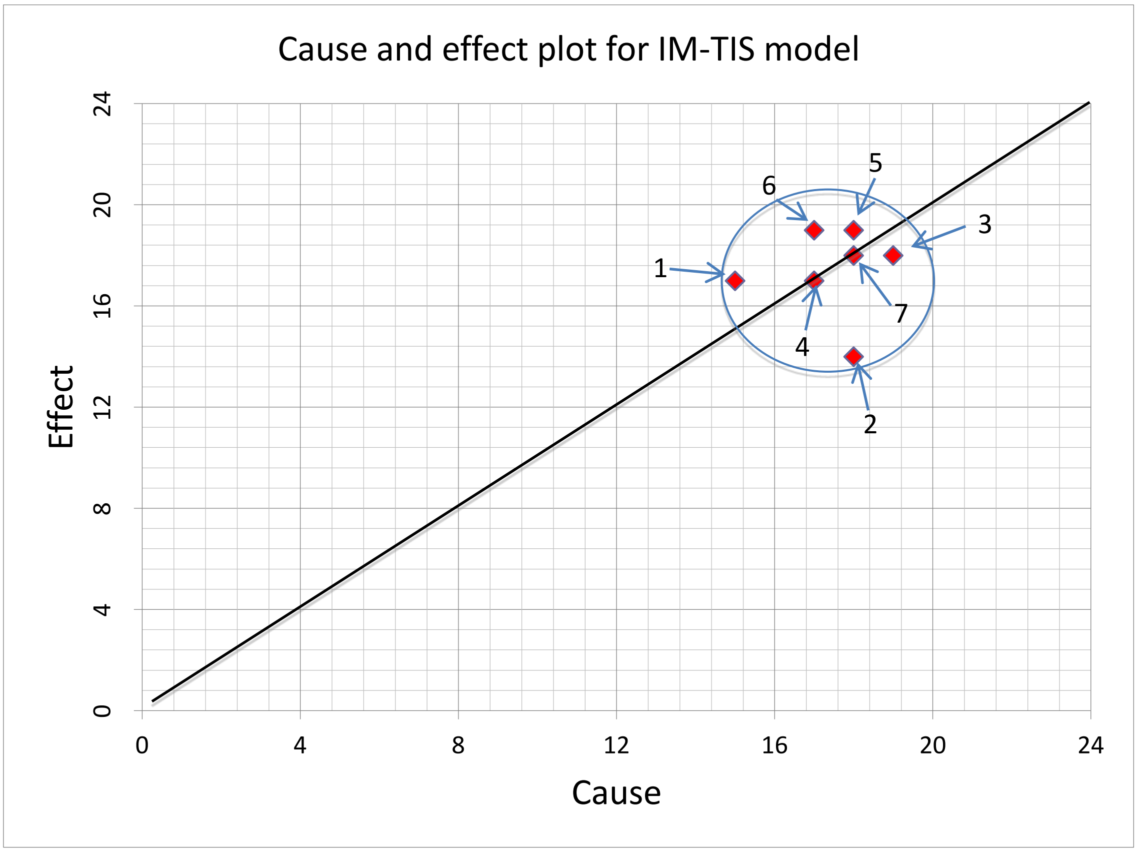


Figure 5.7 the Cause-Effect plot for the IM-TIS model showing functions 1-7.

Hudson (2013) describes four Cause-Effect Plot Patterns; these are described in Table 5.4 below:

Table 5.4. Descriptions of Cause-Effect plots Harrison and Hudson (2006)

Type	Description
Pattern 1	Clustered around the centre of gravity of the points; this is a strongly grouped system.
Pattern 2	Dispersed around the centre of gravity of the points; this is a weakly grouped system.
Pattern 3	In an elliptical zone around the C=E diagonal; this is a system of variable intensity but with similar dominance of subjects.
Pattern 4	In an elliptical zone around the diagonal opposing the C=E diagonal; this is a system of similar intensity but with variable dominance of subjects.

The level of interaction in the system is based on how close to the maximum co-ordinates of (24,24) the system is plotted on the 45-degree cause-effect line. From Figure 5.6 it can clearly be seen that this is a Pattern 1 strongly grouped system, being clustered around the centre of gravity of the points and highly interactive, as the cluster is towards the top of the C=E line. This is to be expected from IM-TIS, as it represents a system where all interactions exist. It is suggested that technological innovation systems should have a high level of interaction between the different functions of innovation in order to be effective and produce the desired outcomes. This system is described as 'ideal', based on the existence of all the interactions identified within the IM-TIS.

The points shown on the Cause-Effect plot are distributed on and around the cause-effect line. It would be unlikely for all the points to exist on the cause-effect line, as that would suggest that all C and E values for the interactions within the system for each subject that are the same. The presence of three subject points on the cause-effect line is due to the high number of Level 3 interactions. The process of ESQ coding is to identify the level of importance each interaction has in contributing towards the desired outcome; in this case, this is the development, diffusion and commercialisation of hydrogen produced from waste within the regional case study zones.

The Cause-Effect plot allows for one further element of the IM-TIS to be extracted. In this strongly grouped system, where many of the C-E co-ordinates are of the same or similar value, determining which subjects are dominant or subordinate is less simple than in more dispersed systems. From the C-E co-ordinates presented earlier in this section and shown in Figure 5.7 co-ordinate sets 1, 2 and 6, representing *knowledge development and diffusion*, *influencing the direction of the search* and *resource mobilisation* respectively, have Cause and Effect co-ordinate values at least two apart in value.

Starting with *knowledge development and diffusio*n, represented by co-ordinates (15,17), the influence (cause) this subject has on other subjects is less than the effects of the other subjects on itself. From this, it can be shown that this is a slightly subordinate subject, the outcomes of which are dependent on the activities and influences of subjects (functions) upon this subject within the system. *Influence on the direction of the search* is represented by co-ordinates (18,14), where the influence this subject has on the system is greater than the influence of the system upon itself and thus it is a dominant subject. *Market formation, entrepreneurial experimentation* and the *development of positive externalities* all present C–E co-ordinates that are equal and appear on the cause-effect line seen in Figure 5.7. Finally, the subject representing the function of innovation, *resource mobilisation*, provides the co-ordinates (17,19). Again, as in knowledge development and diffusion, this subject is subordinate.

5.1.1 Additions to the RES model

The base model of RES has been used to develop IM-TIS. The IM-TIS model goes beyond the RES base to provide further detail of the TIS under investigation. Two further analytical tools were added to the model. Firstly, the "indicators of effectiveness" that show how a system is either successful or failing to allow for action to be taken in the correct place. Secondly, the "coefficient of vulnerability" that provides detail on whether the system is producing positive or negative relationships. These are described in sections 5.2.1 and 5.2.2.

5.1.2 The Indicators of Effectiveness

The three indicators of effectiveness are descriptive indicators that show how the functions have changed or not in the case study, compared to the original system. Indicators include, firstly, information on whether the function has remained dominant, subordinate, even or switched, based on the case study results. The second indicator shows the strength of the function within the system; and the final indicator describes how the overall effectiveness of the system is affected by the changes in the functions. The overall effectiveness of the case study IM-TIS is calculated based on the total ESQ coded interactions that are active within each case study, compared to the originally developed IM-TIS.

5.1.3 The Coefficient of Vulnerability

Finally, the coefficient of vulnerability refers to a correlation coefficient. The coefficient used is Pearson's R coefficient. This correlation coefficient is used to investigate the relationships (Higgins 2005) between the cause and effect of the functions within the IM-TIS case studies: i.e.,

- If there is a relationship.
- Whether the relationship is positive or negative.
- How strong the relationship is.

The correlation coefficient or as it is named here, the coefficient of vulnerability, does not establish causation. The coefficient shows whether there is a relationship between the functions and what type of relationship that is.

The coefficient of vulnerability, shown here as r_{xy}, (where x is the cause and y the effect) is represented by the following equation:

$$r_{xy} = \frac{\Sigma XY - \frac{(\Sigma X)(\Sigma Y)}{n}}{\sqrt{\left[\left(\Sigma X^2 - \frac{(\Sigma X)^2}{n_x}\right)\left(\Sigma Y^2 - \frac{(\Sigma Y)^2}{n_y}\right)\right]}}$$

Results of the coefficient of vulnerability always fall between +1 and -1. A result of +1 shows a perfect positive relationship between the cause and effect co-ordinates of the functions of innovation. A result of -1 shows a perfect negative result. A coefficient of vulnerability result that is negative means that, for example, if the cause of one function is increased there is a predictable decrease in the effect of the function. For a positive result, this means that, as the cause of a function increases, there is a predictable increase in the effect.

The coefficient of vulnerability for the IM-TIS model calculated using the above equation is 1 where a perfectly positive relationship exists between the cause and effect of each function. This means that, as the cause of each function increases, so does the effect. The result of this may be the increased activation of interactions between the functions.

The outputs of the IM-TIS model in case study regions are analysed individually and compared to the IM-TIS model in Chapter 6. The results are also compared to each other and observations for each region made.

5.1.4 Model Limitations

There are currently no reviews of the RES model in the academic literature, only applications. This means that there were particular limitations offered in the literature prior to developing IM-TIS. As noted in section 2.4.1 and 5.1, there are a number of limitations in terms of the functions of innovation framework in its original form. Therefore the discussion of the limitations of the IM-TIS model is based on researcher experience of using IM-TIS throughout this research. In this instance, the matrix subjects were formed of Bergek *et al*. (2008) functions of innovation. However, should different subjects be used or the functions adapted, then the absence of a critical subject may create an invalid system. This would be due to the lack of relationships and interactions from this missing subject. It is important that the matrix development is reviewed to ensure all critical subjects are present.

As suggested earlier in this chapter, the relationships occurring in the matrix subjects may be altered to suit a particular problem or dimension of the TIS. This means that, should different relationships be used within the model to analyse particular technologies or regions, no comparison between these new and different relationships can be made to this original IM-TIS model. The IM-TIS is most effective when the relationships are kept consistent and the technologies or sector under investigation remain the same. This consistency will allow for comparisons to be made between sectors, technologies and regionally.

In the sections of the chapter presented so far, the process undertaken to develop the IM-TIS model has been described. The amalgamation of the RES and functions of innovation models has produced a new model capable of adapting to most technological innovation system problems. In the following chapter, IM-TIS is applied to three case study regions (London, South Wales and Tees Valley) and the results analysed. The following section covers the application of the methods to the three case study regions, providing detailed descriptions of how the model was used and how the results were gathered. Study limitations and conclusions will also be covered.

5.2 Application 1: IM-TIS model to three case studies (London, South Wales and Tees Valley)

In this section, the application of the IM-TIS model to the three case study regions of Tees Valley, South Wales and London is described.

The case study analyses were carried out using a five-step approach. The steps employed are described individually in this section and are as follows:

- In-depth interview
- Analyses of interviews for existence of matrix interactions
- Application of qualitative data to the IM-TIS model
- Outputs of the IM-TIS model
- Key Observations

All steps were applied to each case study region and then the outputs were discussed and compared. Discussion of the comparisons is presented in Chapters 6 and 8 (Case Study Results and Discussion).

5.2.1 The geographical distribution of the case studies

Initially, the case study regions were chosen to represent areas in the UK where regionally unique strategy and policy had been developed to encourage further development of hydrogen from waste activities. This led to the decision to investigate both London and South Wales. London's waste to energy activities are managed by the London Assembly and London's governance structure has galvanised action through the London Hydrogen Partnership (LHP 2010). In South Wales, waste to energy activities have been shaped and promoted by the Welsh Government. Here, sustainable waste management and renewable energy activities are high on the Welsh Government's agenda, leading to the development of the Baglan Energy Park in Port Talbot (One Wales: One Planet, 2009).

Through the process of face-to-face interviews and the collation of secondary data, it became evident at an early phase in the case study development and analysis that few or no commercial developments for hydrogen production from waste were yet either planned or underway in London or South Wales. Bringing together hydrogen from waste innovation systems and interaction matrices created an opportunity to engage with commercial actors, ensuring a complete analysis of the regions. The next step was to explore where hydrogen from waste was commercially active in the regions. This was explored through hydrogen networks, including the SUPERGEN HDelivery Consortium. The activities of Air Products and partners in the Tees Valley were identified in this way and so it became the third case study region.

All three regions exhibit clusters of activities in the hydrogen from waste technological field. Clusters were identified as areas where there were pilot programmes underway, particular government policies for hydrogen in place, university or local government activities around use of wastes for energy or where businesses were investing in hydrogen. These could include the activities of governments and devolved administrations, government funded bodies, as well as academia and business.

5.2.2 In-depth Interviews

To establish the role of different organisations and individuals involved in the technological innovation system, ten in-depth interviews were undertaken. In Tees Valley and South Wales, three interviews were conducted, and in London four interviews were completed.

The organisations in each case study region were chosen based on their involvement with hydrogen projects in the regions. Each individual interviewed provided the opinion of the organisation, but they participated anonymously. The organisations represented are shown in Table 5.5.

Table 5.5. The organisations participating in in-depth interviews.

Tees Valley	Description
SITA Environmental	Energy from waste plant situated at the main Tees Valley industrial park near Middlesbrough.
Impetus Waste	National waste management company working primarily in the north of England.
Air Products	International industrial gases company with plans to develop hydrogen from waste plant in Tees Valley in partnership with Impetus waste.
South Wales	
Environment Agency	National regulator for England and Wales responsible for waste and energy from waste plants.
Glamorgan University, now the University of South Wales	South Wales based university with interest in hydrogen production from waste. Currently running pilot projects at Baglan Energy Park in South Wales.
Wales Automotive Forum	Small organisation representing the Welsh automotive industry. Has a particular interest in hydrogen fuel cells and the production of hydrogen from waste.
London	
Imperial College	London based university with a cross-university Energy Futures Lab and particular interest in hydrogen and hydrogen produced from waste.
Croydon Borough Council	London borough that unsuccessfully trialled a hydrogen from waste project. The project failed due to lack of financial support and human resource pressures.
Elemental Energy	London based energy consultancy that works closely with the London Boroughs, the London Hydrogen Partnership and other interested partners.
London Hydrogen Partnership	London based network of organisations, all working towards achieving a hydrogen future. Contact was from the Greater London Waste Authority.

Initially, five other organisations were also contacted, two in South Wales and three in London, i.e., the Welsh Government, Rank Hovis, London 2012, Camden Borough Council and First Bus respectively. These organisations were not able to participate, but are well known for being active in hydrogen end use or hydrogen production from waste.

The in-depth interviews were developed in order to draw out each participant's thoughts on the use of hydrogen from waste in terms of the functions of innovation.

Additionally, the questions aimed to establish how the different organisations looked for partners and behaved towards each other in the innovation system.

The interviews were conducted either face-to face or via telephone. The choice of how the interview was conducted was made by the individual participating.

The questions used to guide the interviews were approved by the Welsh School of Architecture Ethics Committee and are given in Box 5.1.

Box 5.1: Case Study Questions

1. *What activities are you currently undertaking in relation to hydrogen production from waste? Can you tell me a bit more about these in detail?*
2. *Why did you decide to get involved in these activities?*
   Did you canvass any visions from elsewhere before you began your projects
3. *Are you leading on this work? If No, how did you come to participate in the project?*
4. *Are you working in partnership with anyone else? How did your partnership come about?*
5. *How easy have you found carrying out this work?*
6. *Did you find any barriers to your activities and how did you overcome them?*
7. *Did you have any particular assistance from anyone and what form did that assistance take?*
8. *Have you found it difficult creating or finding a market for hydrogen from waste?*
9. *How do you think the public perceive your work?*
10. *How have you publicised your projects and activities?*
11. *Do you actively facilitate public participation?*
12. *Have you used any social networks to promote your work?*
13. *Do you think that your activities will leave a legacy and if so what shape does this legacy take?*

All of the interviews were recorded using a digital recording device and subsequently transcribed.

5.3 Analyses of interviews for matrix interactions

The transcriptions of the interviews were loaded into ATLAS ti.[1] an assistive tool for coding and analysing qualitative data. The codes used to analyse the qualitative data represented the functions of innovation used as subjects in the IM–TIS model; in addition two further codes were applied:

- barriers to innovation, and
- observations.

These additional codes were used where qualitative elements of the interview transcripts did not fit into the functions of innovation codes, but were considered to inform the development of the technological innovation system.

Once coded, the data were entered into a spreadsheet for each case study region under the codes for the different functions of innovation, barriers to innovation and observations. This process made it easy to establish whether particular interactions or relationships in the IM-TIS model appeared to exist.

5.3.1 Application of qualitative data to the IM-TIS model

Using the coded data, each relationship or interaction in the IM-TIS matrix for each case study was considered. Where an interaction or relationship was shown to exist, that box in the matrix was highlighted; where the relationship did not exist, the box was blacked out.

For example, Figures 5.8 and 5.9 show the IM-TIS model results for South Wales with highlighted and blacked out boxes, respectively.

[1] Details of the ATLAS ti. qualitative data analysis tool can be found at http://www.atlasti.com/index.html

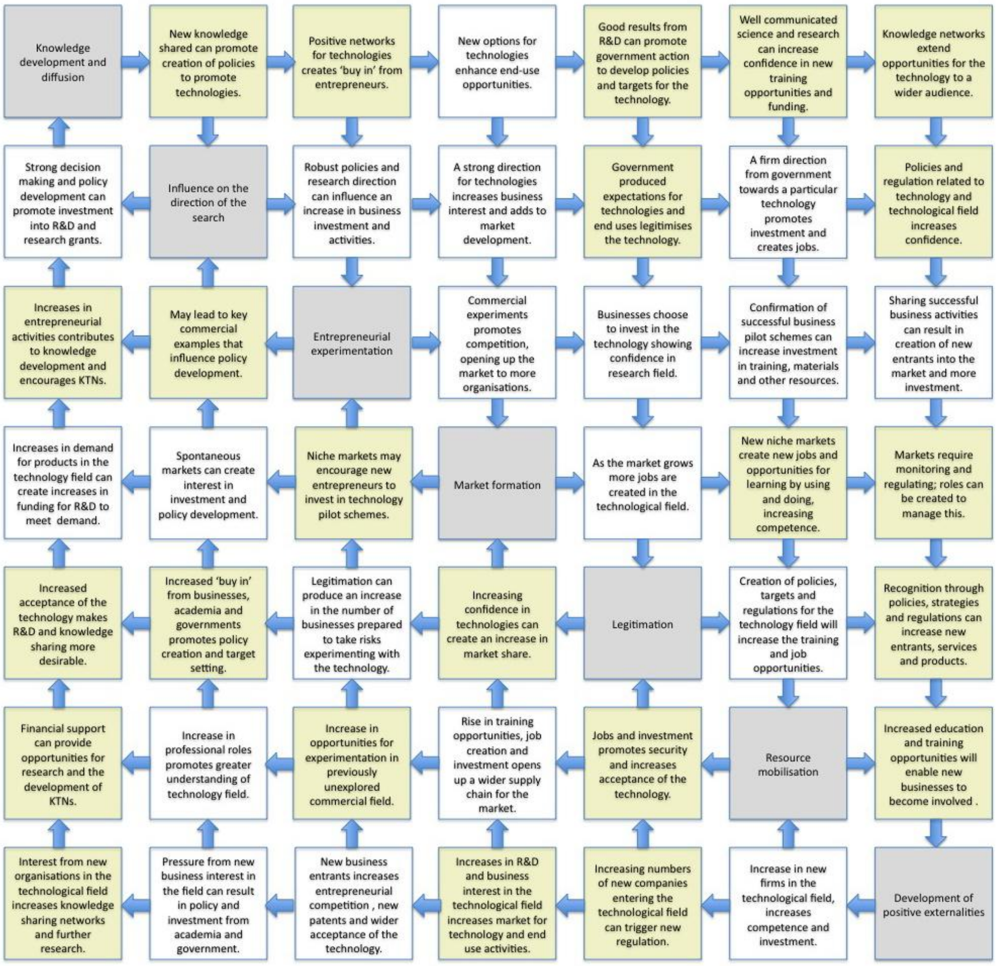


Figure 5.8 H_2fWIM-TIS(SW) with existing interactions or relationships highlighted with a yellow background.

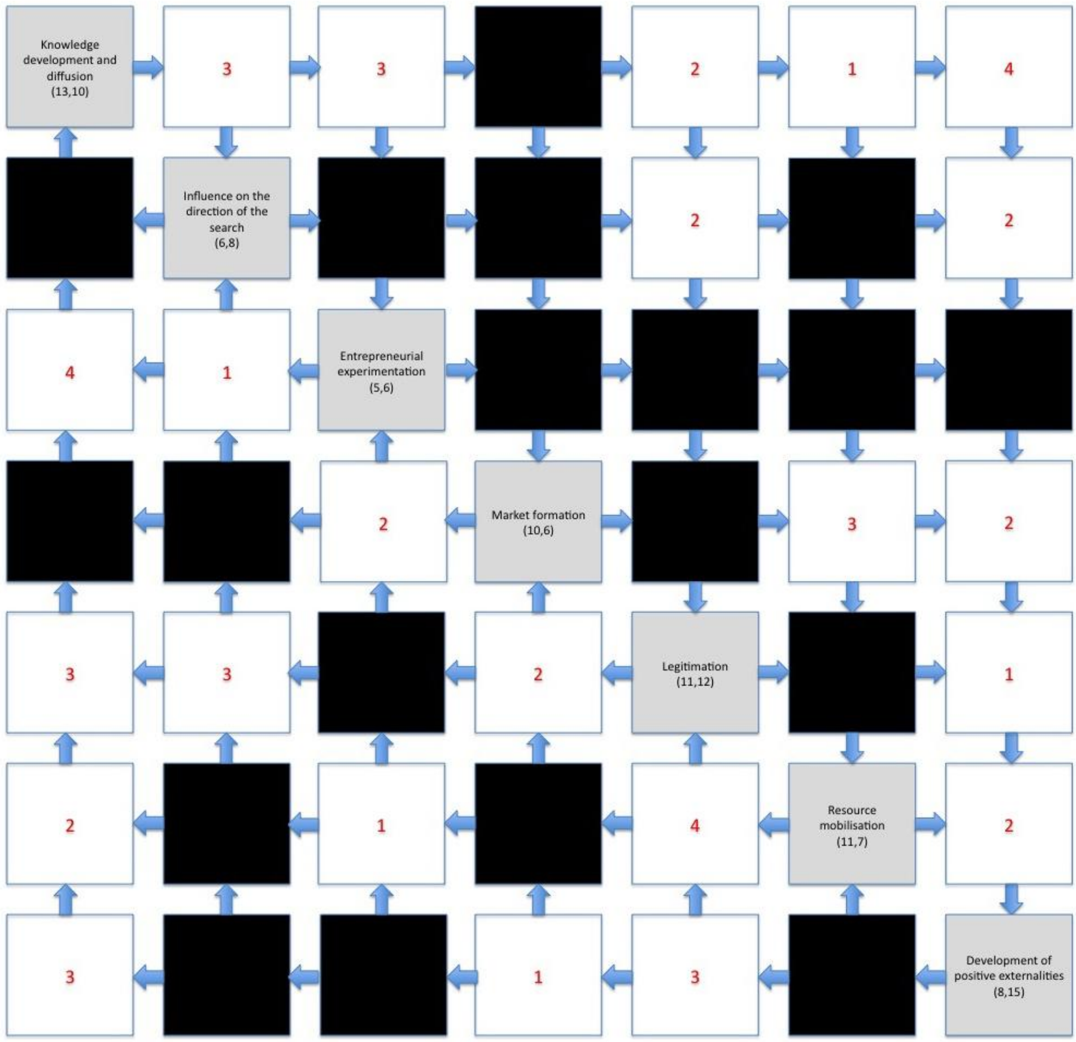


Figure 5.9. H_2fWIM-TIS(SW) with non-existent interactions or relationships blacked out.

This process enabled the production of factor co-ordinates for each of the functions of innovation and an overall matrix total to be produced. Following this process the model was applied, as described in section 5.1, and the additional elements of the model calculated as described in section 5.2.

5.3.2 IM-TIS model outputs

When all of the qualitative data and all of the interactions or relationships in the IM-TIS model had been considered, the following were produced for each case study region:

- Cause-effect graph.
- ESQ distribution graph.
- Dominant and subordinate factors.
- Coefficient of vulnerability for the factors (functions of innovation) in each case study region.
- Index of effectiveness for the case study region.

5.4 Application 2: Pathway identification and use in the IM-TIS matrix – Methodology for the illustrative example

The application of the IM-TIS model to assess the typologies and effectiveness of the regional technological innovation systems for hydrogen from waste is a second application for IM-TIS.

This secondary IM-TIS application identifies mechanism pathways (Hudson & Harrison 2006) that may support further activation of interactions within IM-TIS. For an individual aiming to deliver policies within a case study region, this approach could be presented as an assistive tool. It may be possible for an assessor who could be a researcher or policy developer to identify pathways utilising relationships that are known to exist within the IM-TIS system to galvanise action in other interactions. It is suggested that increasing activities in the interactions shown in IM-TIS may increase the effectiveness of each interaction and subsequently the system.

In Chapter 7, the worked example of this IM-TIS application will relate to the London region, an area known to have explicit policies for hydrogen production from waste. This is the only region in the UK where this is known to be the case.

The ESQ coding used in the development of IM-TIS is used in this worked example to show the impact that each pathway identified may have. The ESQ coding reflects the importance (Hudson & Harrison 2006) of the pathways through the interaction. The intensity of the pathway is equal to the total ESQ coded interactions that are active or become activated through the pathways. An example of pathway development shown in a section of the IM-TIS model is given in Figure 5.10.

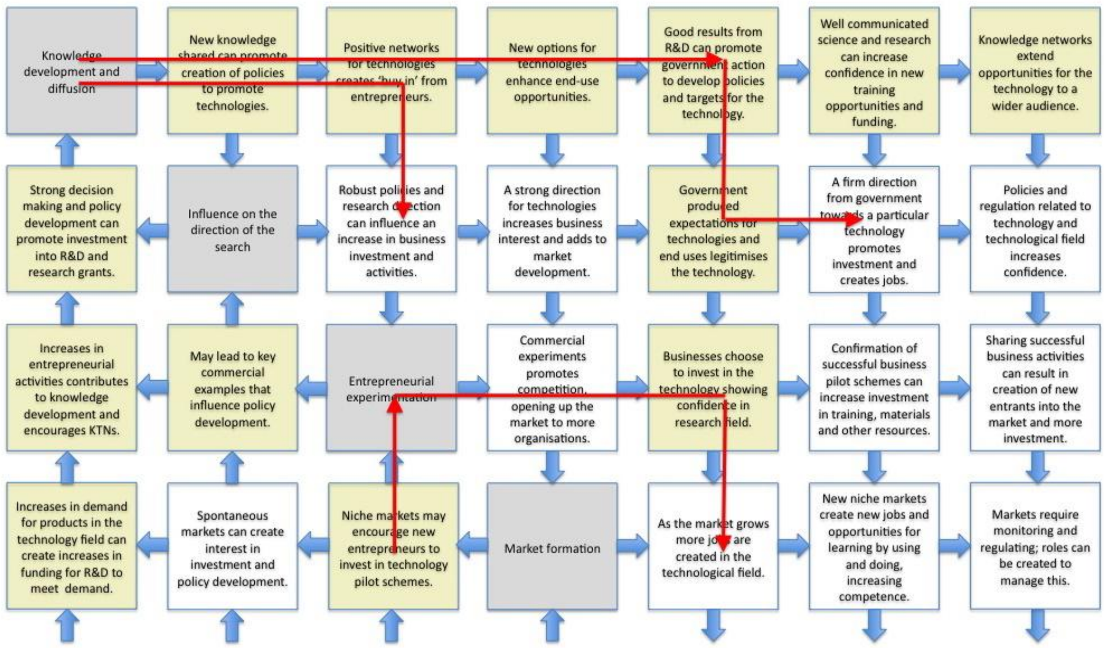


Figure 5.10. A section of the London IM-TIS application with pathways highlighted in red (Example taken from Chapter 7 and discussed in detail there)

As each interaction within the pathway is addressed, the assessor is able to identify activities that may support this interaction. These results may then be used to inform decision making that might increase the effectiveness of the IM-TIS being examined (hydrogen from waste in the London region) and the delivery of regional policy.

Chapter 7 will illustrate how by using IM-TIS as described above it is possible to incorporate the findings of the Q methodology (presented in Chapter 4) with IM-TIS, to produce a method that effectively assists in the assessment and review of policies. It will be shown how the use of the group identities may provide insight into how various interactions may be achieved and why TIS actors behave in certain ways. The Q methodology identities in this instance are considered similar to those of the actors in the hydrogen from waste TIS in London. It is, however, important to note that one limitation of Application 2 of IM-TIS and Q methodology to this London Case study is that the Q methodology does not represent group identities in London. It can only develop group identities within the cohort examined; however, this does include some members of the London case study. This is described in detail in section 3.3.1

The process is worked through in the illustrative example in Chapter 7, showing step-by-step considerations that may achieve the development, diffusion and commercialisation of hydrogen from waste technologies in the London example.

* * * * *

In this chapter, the development and two applications of IM-TIS have been described. The development of the IM-TIS model aims to address the sub research question: *What does the comparison (Aim 2) between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?*

The results of the application of IM-TIS as described in this chapter are given in Chapter 6 (Case Studies) and Chapter 7 (worked example of IM-TIS pathways including Q Methodology in a 'real' situation).

5.5 References

Bergek A., Jacobsson S., Carlsson B., Lindmark S., Rickne A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (2008) 407–429

Harrison J.P., Hudson J.A. Comprehensive hazard identification in rock engineering using interaction matrix mechanism pathways. The 41st US Symposium on Rock Mechanics. 2006

Hudson J.A. 2013. A review of Rock Engineering Systems (RES) applications over the last 20 Years. *Rock Characteristion, Modelling and Engineering Design Methods.* (Eds. J.A. Hudson, X.T. Feng, Tan F.): Proc SINOROCK2013 ISRM Symposium, Shanghai, China, June 2013.

Johnson A. Functions in innovation system approaches, mimeo. Department of Industrial Dynamics, Chalmers University of Technology, Sweden. 1998.

Temel T., Janssen W., Karimov F. (2002) The Agricultural Innovation System of Azerbaijan: An assessment of institutional linkages. ISNAR Country Report 64. Temel, T., Janssen W., Karimov F. Systems analysis by graph theoretical techniques: assessment of the agricultural innovation system of Azerbaijan. Agricultural Systems 77 (2003) 91–116

Webler T., Danielson S., Tuler S. 2009 Using Q method to reveal social perspectives in environmental research. Greenman MA: Social and Environmental Research Institute. www.seri-us.org

Welsh Government Website – details of WG strategies. Accessed 01/04/2013 http://wales.gov.uk/;jsessionid=A81CD2E7A5B4CF1D93DA00E4800C9B46?view=Search+results&lang=en

Welsh Government. Towards Zero Waste: The overarching waste strategy for Wales. 2010. Welsh Government Publication.

Welsh Government. Wise about Waste 2001: the national waste strategy for Wales. Welsh Government Publication.

6 Results – Description of Case Study Regions, Tees Valley, South Wales and London, and Application of IM-TIS model to Each Region.

The results of the Q methodology were presented in the previous chapter. These results contributed to characterising types of individuals involved in the technological innovation system for the sustainable production of hydrogen from waste. The three types identified may be considered as broadly representative of the professionals working within the actor organisations in the case study regions. In this chapter, the focus moves from the role of people in the innovation system to the role of organisations in the system. The case studies discussed in this chapter aim to investigate how organisations operating in each case study region have contributed towards the future potential of hydrogen from waste.

The application of the IM-TIS methodology and results presented here are intended to meet the requirements of Aims 1 and 2, as presented in the research flow diagram in the front pages of this thesis and Chapter 1 (Introduction):

1. To create a model technological innovation system that can be applied to the sustainable production of hydrogen from waste and which incorporates the perspectives of experts working in the technological field.
2. To apply the model to regional case studies and make comparisons between ‘real’ and the ‘model’ technological innovation systems in the field of hydrogen production from waste.

Addressing these aims contributes to answering the second research sub-question: *What does the comparison (Aim 2) between ‘real’ and the ‘model’ technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?*

The analysis of real situations is particularly relevant to these results—as all of the case studies are investigations of situations where technological innovation systems are emerging. Applying the new IM-TIS model to these case study regions offers an opportunity to identify how the model may need to be adapted should it not reflect real situations as found in these regions. The investigation may also increase the understanding of the roles that actors play in each regional innovation system, along with the influence that they may have on others within the system. The results of the case studies will therefore contribute to the overarching research question: *"What role might hydrogen from waste have in a future energy system?"*

The results of three case study investigations that took place throughout the summer of 2012 are presented in this Chapter. The case studies were undertaken in order to identify, characterise and understand the technological innovation system for the production of hydrogen from waste in the UK regions of South Wales, Tees Valley and London (the regions are shown in Figure 6.1).

6.1 Aims of the Case Studies

The aims of these case studies are as follows.

1. Describe and analyse the technological innovation system for the sustainable production of hydrogen from waste in the regions of South Wales, Tees Valley and London.
2. Make key observations for each of the regions.
3. Make comparisons of the differences in each region and identify how these differences impact on the effectiveness of the innovation system.
4. Address the overall research and research sub-questions cited earlier.

These case studies focus specifically on the technological dimension, identifying the interactions or lack of them between the actors and institutions. By analysing these interactions in each region, the role of the innovation system in supporting new and emerging technologies will become clearer.

6.2 Scheme of analysis

Each of the three case studies is analysed by applying the IM-TIS model to the regions; details of the IM-TIS model were provided in Chapter 5 (Development and Application of IM-TIS model). The results of each case are provided individually. A comparison of results from the three cases is given in section 6.9.

6.2.1 The nature of the investigation

Innovation systems are increasingly being described as a structured model for economic growth and development. Technology advancement and human advancement go hand in hand with innovation theories focusing on human knowledge creation and diffusion (Temel *et al.* 2002).

These case studies apply combined conceptual ideas and models to real life situations where TIS are emerging. The application of the models is intended to confirm, refute or refine the concept and create a new understanding of how the TIS develops and how new pathways can be created to improve effectiveness.

6.2.2 Case Study Regions

Figure 6.1 is a map of the UK that identifies the location of the three case study regions. The regions were chosen as described in section 5.2.1. The cluster activities occurring in the case study regions were:

- regional aspiration,
- government direction through strategy and policy development,
- provision of funding opportunities,
- commercial and academic pilot programmes,
- research activities, and
- local government planning support.

The cluster activities given above are supported in each of the regions. However, there are currently no commercially active hydrogen from waste facilities in the UK and the representation made in the clusters are through pilot research activities or commercial aspirations and not actual plant development.

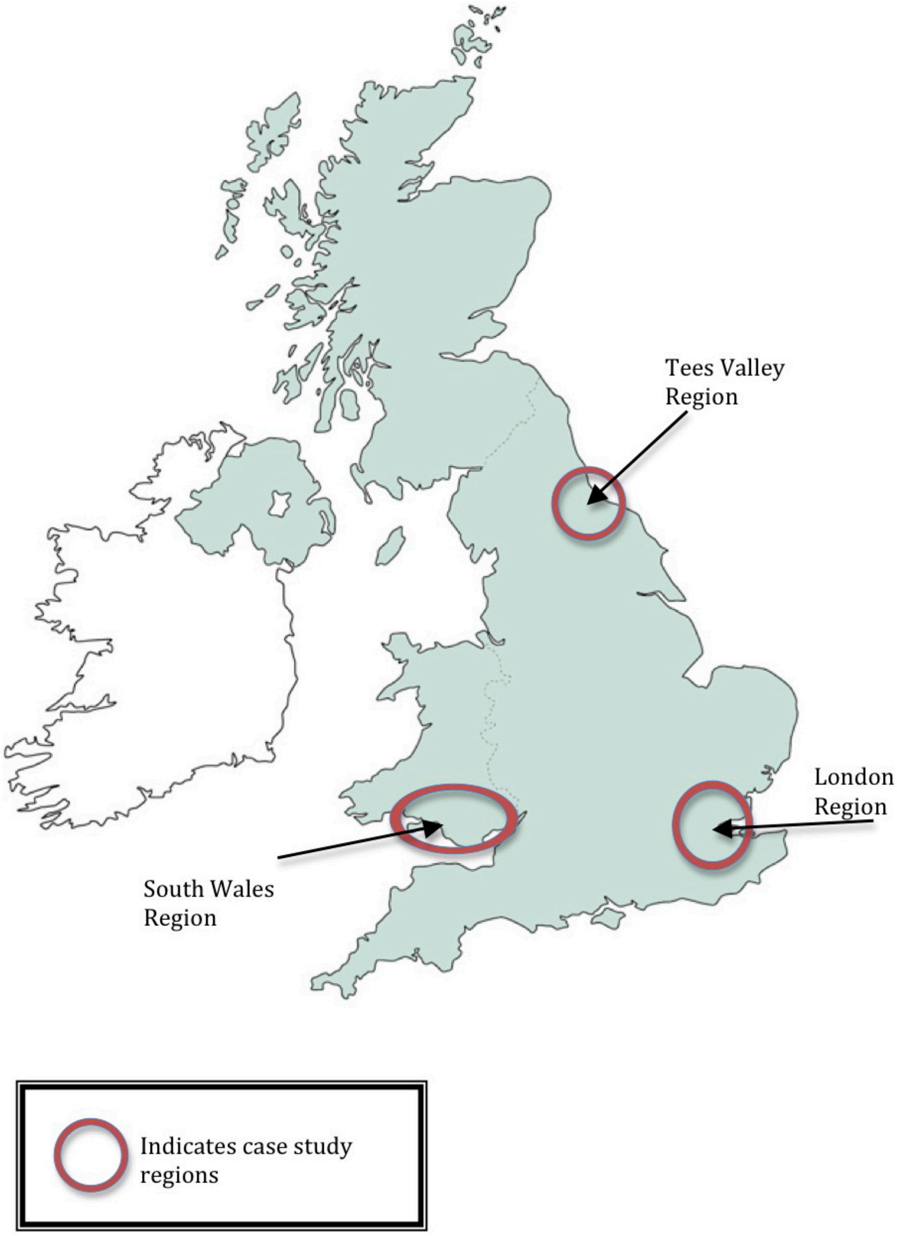


Figure 6.1. The case study regions in the UK.

6.2.3 Participating organisations in each case study region

Table 6.1 provides details of the organisations whose employees or representatives participated in the in-depth interviews in each of the three case study regions. As noted, the individuals interviewed agreed to participate anonymously and therefore only their organisation is recorded.

Table 6.1. Organisations participating in case study interviews.

Tees Valley	Description
Sita Environmental	Energy from waste plant situated at the main Tees Valley industrial park near Middlesbrough.
Impetus Waste	National waste management company working primarily in the north of England.
Air Products	International industrial gases company with plans to develop hydrogen from waste plant in Tees Valley in partnership with Impetus waste.
South Wales	
Environment Agency	National regulator for England and Wales responsible for waste and energy from waste plants.
Glamorgan University	South Wales based university with interest in hydrogen production from waste. Currently running pilot projects at Baglan Energy Park in South Wales.
Wales Automotive Forum	Small organisation representing the Welsh automotive industry. Has a particular interest in hydrogen fuel cells and the production of hydrogen from waste.
London	
Imperial College	London based university with an energy futures department and particular interest in hydrogen and hydrogen produced from waste.
Croydon Borough Council	London borough that unsuccessfully trialled a hydrogen from waste project. The project failed due to lack of financial support and human resource pressures.
Elemental Energy	London based energy consultancy that works closely with the London Boroughs, the London Hydrogen Partnership and other interested partners.
London Hydrogen Partnership	London based network of organisations all working towards achieving a hydrogen future. Contact was from the Greater London waste authority.

6.3 Tees Valley Case Study

Tees Valley, often referred to as Teeside, is the name given to a region of the north east of England including the towns of Middlesbrough, Stockton-on-Tees, Clevedon, Redcar, Hartlepool and Darlington. The Tees Valley area has a population of 875,000 and is 304 square miles in area, as at the 2011 census (Tees Valley 2013).

The specific area of Tees Valley being investigated as part of this case study is the large industrial park just outside Middlesbrough, which is part of the Tees Valley Unlimited Project described below. Historically, this region accommodated heavy industries, such as iron and steel production (Simpson 2009). However, in recent years, the heavy industry has declined and unemployment increased. This has proved problematic for the region: deteriorating standards of living and lack of investment led to the Gross Value Added (GVA) per capita for the region being only 77% of the national average in 2009. This situation prompted the development of Tees Valley Unlimited, an organisation made up of partners from the public, private, civic and community sectors. This organisation continues to build on the work of Tees Valley Vision 2002 (Tees Valley 2002), which can be seen in Tees Valley (2013).

The Tees Valley industrial region is now home to a variety of different industries, *inter alia:*

- the Petrochemical Cluster—the largest integrated chemical complex in the UK and the second largest in Europe;
- the Teeside Power Station—one of the World's largest combined cycle gas turbine power stations, which produced up to 1875MW in 2011. However a recent news article (Northern Echo 2013) reported that the power station had ceased power production.
- Teesport port—the fourth largest in the UK and handles eight percent of the UK's container traffic.

Together these three organisations represented approximately 71,000 jobs in 2011. In addition to these industries, Tees Valley is also home to the Centre for Process Innovation and the Institute of Digital Innovation, both supporting business and innovation in the region (Tees Valley Unlimited 2011).

In their Economic and Regeneration Statement of Ambition (Tees Valley Unlimited 2011), Tees Valley Unlimited stated two key ambitions, as follows:

1. Drive the transition to the high value low carbon economy; and
2. Create a more diversified and inclusive economy.

This case study is particularly concerned with the first of their ambitions, where they aim to (Tees Valley Unlimited 2011):

- *"Facilitate pilot projects, using the existing assets and skill base, to test and scale up new and novel low carbon technologies through innovation such as developing a carbon capture and storage network for existing industries and new users or resource recovery through anaerobic digestion.*

- *Building on the Tees Valley Industrial Programme, invest in innovative delivery vehicles to bring forward land for development, upgrade utilities, run steam and heat networks and remove barriers to investment, focused around the spatial area of the North and South Tees."*

There is a dovetailing between these ambition statements and the strategic objectives of the UK Government, as will be explained below. Unlike London and South Wales, Tees Valley is not governed by a devolved administration. In Tees Valley, Tees Valley Unlimited is positioned within a broader policy landscape, which will now be described. The Technology Strategy Board (TSB) identifies businesses as the key to delivering innovation and provides a number of different media to support businesses in research, development and the creation of demonstration and pilot projects (TSB 2013). An example of this is SMART—a grant that is available to small and medium sized businesses to support research and development activities in science and engineering technological fields. These activities should be contributing to strategically important products, services and processes, such as energy and transport (SMART 2012).

The TSB presents itself as a non-departmental government body. It was created by government and is funded by various UK government departments and the devolved administrations. The TSB provides guidance to government that can impact on the funding streams to different technological fields. The activities of the TSB are reflected in the first of the two ambition statements generated by Tees Valley Unlimited and they envision that the research and development pilot projects could be funded by the TSB and possibly by some broader European Union grant provision.

The funding programmes issued by the TSB are backed by evolving policy and strategy developments of the UK Government. Two key documents that provide the policy backdrop to the promotion and encouragement presented by Tees Valley Unlimited in terms of hydrogen production from waste are the UK Renewable Energy Roadmap (DECC 2011) and the Anaerobic Digestion Strategy and Action Plan (DEFRA 2011). The activities in Tees Valley are not only a product of these strategies. The Waste Strategy for England (DEFRA 2007) and its 2011 review (DEFRA 2011a), along with the UK Innovation and Research Strategy for Growth (DECC 2012), also provide pertinent instructions for the region of Tees Valley, as described below.

The specific policy position that Tees Valley Unlimited chooses to promulgate, driving businesses and other organisations wishing to invest in the region towards low carbon technologies is:

1. In its UK Renewable Energy Roadmap, the UK Government has stated that they have a goal to generate 15% of UK energy consumption from renewable sources by 2020 (DECC 2011 pg: 9), to comply with the EU targets introduced in the 2009 EU Renewable Directive (EU Parliament 2009). In addition, the Roadmap refers to reducing the cost of renewable technologies and levelling the playing field through supporting learning and technological breakthroughs by use of subsidies (DECC 2011 pg: 19). Finally, in the Roadmap specific attention is given to bioenergy as a fuel of the future. Hydrogen from waste can be classified as bioenergy in cases where the feedstock for the creation of hydrogen comes from waste

biomasses. The Roadmap concludes that. from the evidence gathered, bioenergy for use in transport fuels should be increased to 5% of the UK total by 2014 (DECC 2011 p. 26).

2. In the policy summary presented in section 2.1, EU and UK policies are given that promote the use of wastes to create energy along with the use of renewable energy sources, such as hydrogen. These policies are also relevant to Tees Valley.

The first ambition statement from Tees Valley Unlimited identifies anaerobic digestion as an advantageous opportunity for resource recovery from wastes. In 2011, the UK Government released the Anaerobic Digestion Strategy and Action Plan. The strategy provides a summary of fifty-six actions to enhance the utilisation of anaerobic digestion in the UK. These actions fall into three groups: improving our knowledge and understanding, smarter working models, and regulation and finance. This means that in Tees Valley the ambition statements (if realised) would contribute to achieving the UK vision for renewable energy and anaerobic digestion (DECC 2011; DEFRA 2011).

6.3.1 Participating Organisations

The region of Tees Valley was chosen as a case study due to the strategic decision by Air Products to open a hydrogen from waste plant in the region. The partnering waste management company participating in this project is Impetus Waste. Both of these organizations took part in this case study investigation. Further to these organizations and already operating an existing energy from waste plant in Tees Valley, SITA Waste Management also took part. Although already heavily investing in energy from waste in Tees Valley and committed to increasing efficiencies (SITA UK 2012) at their Tees Valley site, SITA are not considering adapting their processes or activities beyond current capabilities and do not make hydrogen gas. However, it was felt that SITA's experience on the ground in Tees Valley offered a valuable contribution to the case study. SITA have developed their site considerably over the past five years and have a good understanding of the difficulties in infrastructure and development that may accompany any hydrogen from waste developments.

The following section provides essential background information about the organisations participating in the Tees Valley case study region. The results of the application of the IM-TIS model in Tees Valley are given in section 6.4.

6.3.2 SITA Waste Management

SITA UK was established in 1988 and is now part of the larger firm Suez Environment. It manages approximately seven million tonnes of waste per annum in the UK through landfill, composting, energy from waste and recycling (SITA UK 2013). In 2011, the SITA energy from waste plants generated 700,000 megawatt hours of electricity. SITA UK articulate their vision of living in a society where there is no more waste. This vision builds on the concept of the circular economy and identifies an ideal model where waste management services are linked to production and consumption (SITA UK 2012). The circular economy concept is described by Chatham House (Chatham House 2012) as transforming the function of resources in the economy. Waste from factories would become a valuable input to another process and products could be repaired, reused or upgraded instead of thrown away. According to SITA UK, this vision has led them to invest in developing uses for their landfill gases and better utilising the product of their energy from waste facilities (SITA UK 2011).

SITA UK (2013) states that it is in the process of growing its energy from waste and landfill gas activities; through their combined efforts these sites are capable of powering approximately 220,000 homes per annum. At the present time, SITA has thirty-six landfill sites acting as biomethane fuel plants. SITA also claims to be the first waste management company in the UK to produce biomethane fuel for transport. SITA operate energy from waste plants in Tees Valley, the Isle of

Man and Kirklees: all are designed to generate electricity to be fed into the national grid.

The energy from waste plants in Tees Valley is intended to use feedstock that is made up from materials that are not recyclable by the local authorities supplying the Tees Valley Plant. However, the site visit carried out as part of the case study revealed that, in practice, the feedstock is made up of most types of municipal solid wastes including recyclable materials. This is not necessarily a reflection on the SITA plant as recycling is expected to occur on the doorsteps (SITA UK 2012a). However, low recycling rates in the region result in large amounts of recyclable materials being delivered to and treated through the energy from waste plant (SITA UK 2012a).

6.3.3 Impetus Waste

Impetus Waste is the commercial waste management partner with Air Products for their Teeside hydrogen from waste project. Impetus specialises in domestic, commercial, industrial and hazardous waste management, handling approximately 500,000 tonnes of waste per annum. Impetus describes its main objective as seeking alternative treatments for waste (Impetus Waste 2013) and visualises itself as ideally placed for creating new opportunities for energy from waste and encouraging the development of new and emerging technologies from both energy and waste sectors. On Teeside, Impetus have secured planning for a 1020 megawatt combined cycle gas fired power station. They aim to identify and implement synergistic innovation and technology development whereby energy is created, and approximately 500,000 tonnes of waste per annum are diverted from landfill.

6.3.4 Air Products

Air Products is considered to be one of the key organisations leading in the development of the hydrogen economy (LHP 2012) and they are members of the London Hydrogen Partnership and the Scottish Hydrogen and Fuel Cell Association. Air Products is an international corporation that specialises in a number of different industrial practices, one of which is the production of hydrogen and development of its associated infrastructure. In 2012, it had approximately 18,900 employees in forty countries and an annual turnover of $10.1 billion (Air Products 2012a).

Air Products have been cultivating their activities in the hydrogen sector for over fifty years, developing their first hydrogen fuelling station in 1993 (Air Products 2011). The corporation participated in a number of projects focussed on hydrogen as a transportation fuel, including hydrogen buses in London in 2012 and Beijing in 2008, as part of the Olympics demonstration projects.

The interview with a representative (Air Products 2012) from Air products confirmed that California Air Products is supplying hydrogen from the anaerobic digestion of wastewater. The facility produces enough hydrogen for the fuelling of 25–50 cars per day and generates 250 kilowatts of electricity to power the wastewater facility. This facility is a first for Air Products and is an expansion of feedstock types used in the production of sustainable hydrogen. Building on the success of this facility in California, Air Products has been investigating new feedstocks for hydrogen in the UK and initial planning is underway for the development of a gasification waste plant on Teeside. The proposed plant on Teeside differs from the Californian plant in that hydrogen produced is likely to originate from the gasification of waste.

As stated in the interview, the new plant in Tees Valley is not being designed specifically as a hydrogen from waste plant, but this has been recognised as one of the potential opportunities on the site (Air Products 2012).

6.4 Application of IM-TIS model to Tees Valley Case Study – H_2fW IM-TIS (TV)

In the Tees Valley case study region, three in-depth interviews were carried out with members of the organisations described in the previous section. The interviews were digitally recorded, transcribed and analysed. Details of the development and qualitative analysis of these interviews is provided in section 5.2.

6.4.1 Results of qualitative data entry into IM-TIS model

The following two Figures 6.2 and 6.3 show the existence of relationships and interactions as described in the IM-TIS model. The existence of the relationships was established following the analysis of the transcriptions of the in-depth interviews. It is accepted that the analysis of the interviews is subjective and their content might be interpreted differently by different researchers; however, the relationships identified are considered in this instance to reflect the case study regions based on the qualitative data obtained. **Larger versions of all the Figures containing matrices used in all case study regions can be found in the IM-TIS Matrix portfolio complementing this thesis**.

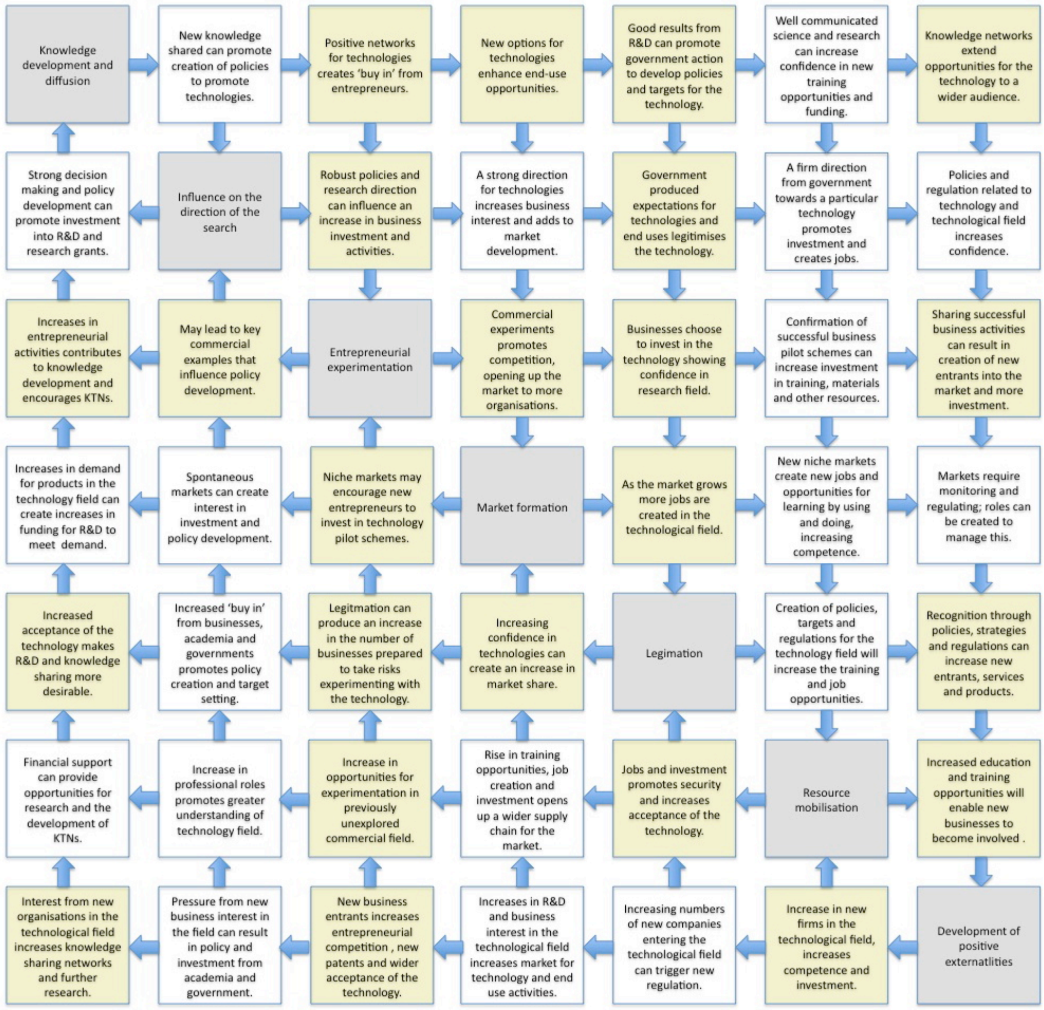


Figure 6.2. Existing relationships highlighted in the IM-TIS model produced from qualitative data H_2fW IM-TIS (TV).

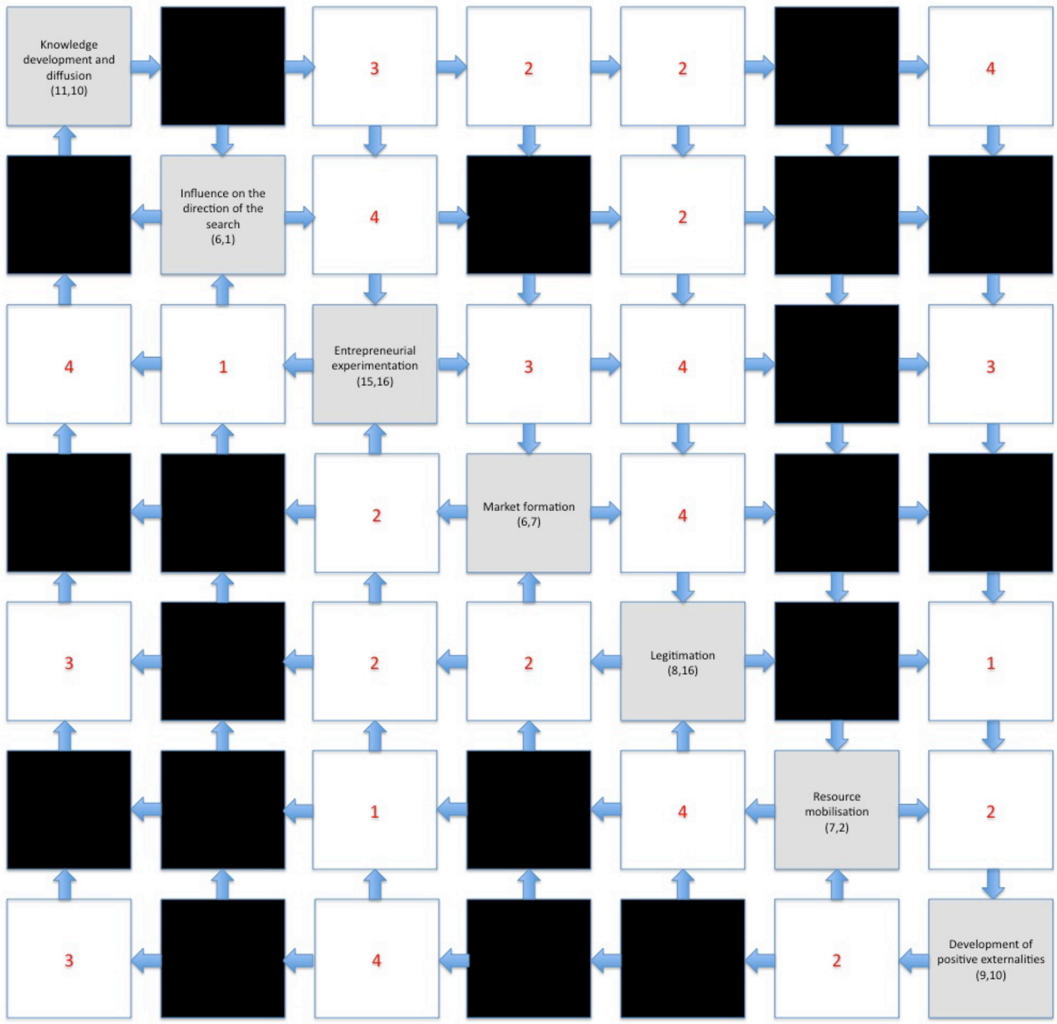


Figure 6.3. Blacking out of the non-existent relationships and interactions in the IM-TIS model, and their effect on the cause-effect co-ordinates for the functions of innovation in H_2fW IM-TIS (TV).

From Figure 6.3, the co-ordinates for the functions of innovation in the H_2fW IM-TIS (TV) were produced and subsequently the cause-effect graph (Figure 6.4) and ESQ distribution graphs (Figure 6.5) for the Tees Valley case study. The co-ordinates for the functions and their ranks are shown in Table 5.1.

Figure 6.4 provides significant detail about the role of the functions of innovation within the emerging TIS for Tees Valley. The cause-effect graph shows a distributed system in terms of interactive intensity with the majority of functions appearing lower down the main diagonal cause=effect line than the results of the original IM-TIS model shown in Figure 5.4. This means that this system presents functions that are of variable interactive intensity. It cannot be said that the functions are weakly grouped, as they show clustering around four of the functions, including: *Knowledge development and diffusion*, *Market formation*, *Legitimation* and *Creation of positive externalities*. However, due to the position of the remaining three functions, this TIS cannot be described as strongly grouped either. As a result, this cause-effect graph shows an emerging TIS, where the functions have variable dominance with moderate interaction. Furthermore, the positioning of the functions lower down the cause–effect line compared to the outputs of the original IM–TIS model implies a less effective TIS.

Table 6.2. Original IM-TIS function of innovation co-ordinates.

Subjects (Functions of Innovation)	C–E Co-ordinates
1. Knowledge development and diffusion	(15,17)
2. Influence on the direction of the search	(18,13)
3. Entrepreneurial Experimentation	(19,18)
4. Market Formation	(17,17)
5. Legitimation	(18,19)
6. Resource Mobilisation	(17,19)
7. Development of positive externalities	(18,18)

Below in Table 6.3 are shown the rank and position of the functions of innovation in the IM-TIS model, once the qualitative data has been entered into the model.

Table 6.3 the functions' co-ordinates and rank for the H2fW IM-TIS (TV) case study

Function of Innovation	Co-ordinates	Rank
1. Knowledge development and diffusion	11,10	Dominant
2. Influence on the direction of the search	6,1	Dominant
3. Entrepreneurial experimentation	15,16	Subordinate
4. Market Formation	6,7	Subordinate
5. Legitimation	8, 16	Subordinate
6. Resource mobilisation	7,2	Dominant
7. Creation of positive externalities	9,10	Subordinate

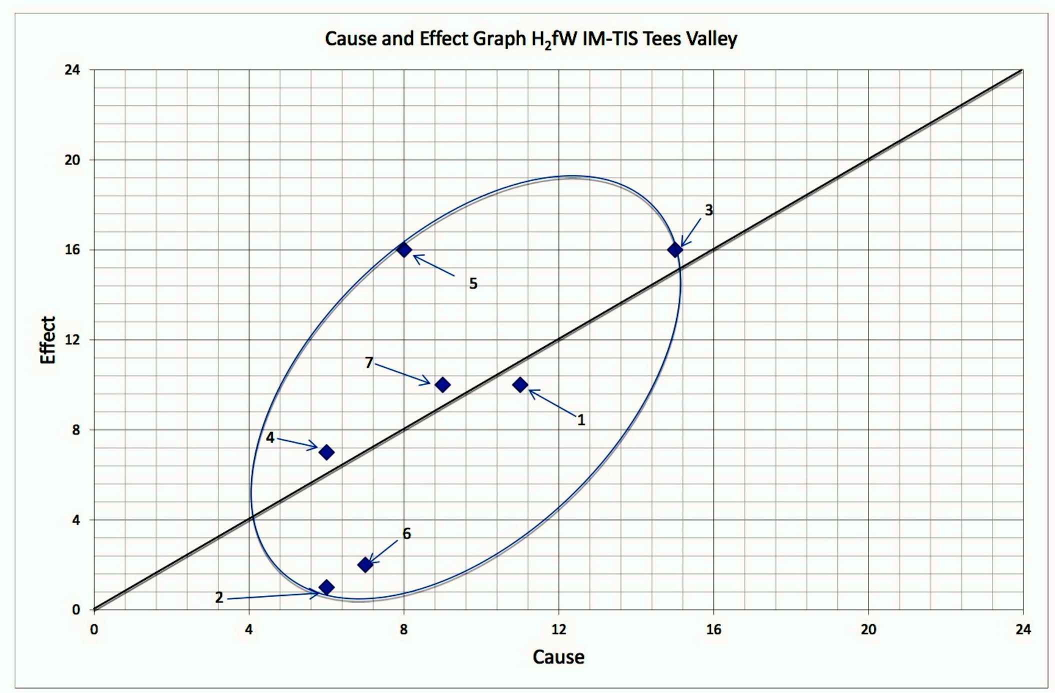


Figure 6.4. Cause-effect graph for the H_2fW IM-TIS (TV) case study functions 1-7.

The ESQ distribution in Figure 6.5 below clearly shows that the most frequently occurring interactions and relationships from the IM-TIS model for TV are coded as Level 2 interactions. The ESQ interaction coding has been described in Section 5.1. The original IM-TIS model and its initial outputs are also described in section 5.1 and has a higher proportion of Level 3 interactions present, indicating a more successful TIS. This graphical representation of the H_2fW IM-TIS (TV) provides further indication that the emerging TIS in Tees Valley is currently of a relatively lower effectiveness.

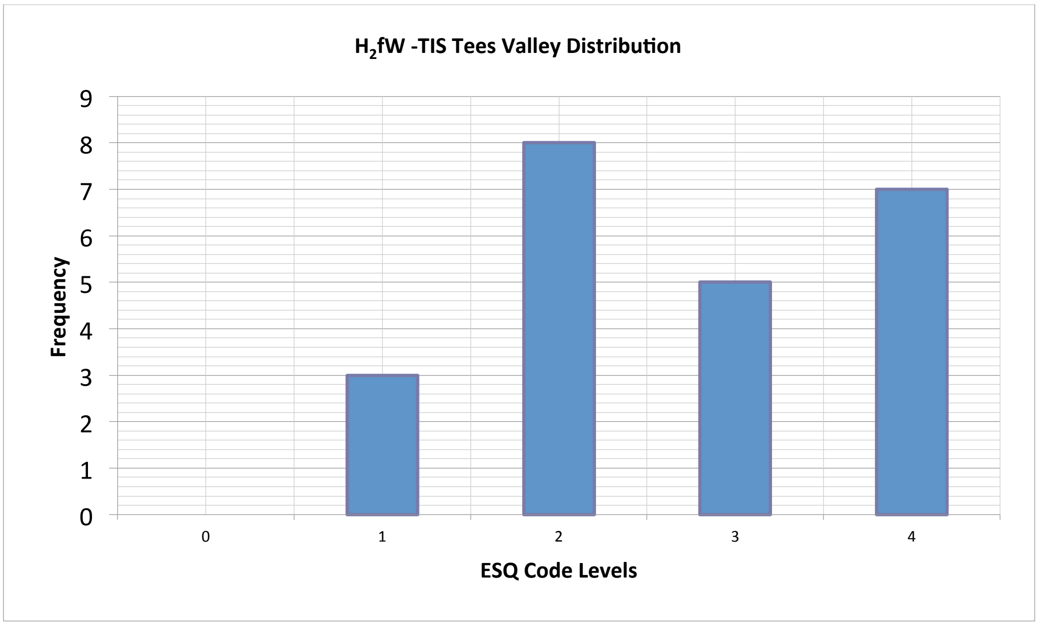


Figure 6.5 ESQ coding distribution of H2fW IM-TIS(TV)

Table 6.3 provides details of the rank and position of the functions within the Tees Valley case study. The co-ordinates denote three dominant variables and four subordinate variables. In terms of the IM-TIS model and the effectiveness of a technological innovation system, variability of dominance is a positive sign for the future of the TIS because if all of the functions are dominant or subordinate the system is more likely to fail, as each function does not have to rely on its relationship with other functions to be successful. All functions would in effect be acting for their own benefit or in the case of subordinate functions requiring action and not acting for the overall system.

To finalise the evaluation of the effectiveness of the H2fW IM-TIS(TV) model, the Indicators of Effectiveness (IoE) are explained for each function in the system, along with the overall Coefficient of Vulnerability (CoV) for the system as a whole. The IoE for each system function are presented in Table 6.4. This is followed by the calculations for CoV and the overall effectiveness. The overall effectiveness is the percentage effectiveness of the whole system compared to the original IM-TIS system.

CoV is the correlation coefficient or Pearson's 'r' and shows the relationship between the functions H2fW IM-TIS(TV). Closeness to 1 indicates the correlation between the cause and effect components of the systems and their proximity to the original system, where there is a positive relationship between all functions in the system. Whereas, proximity of the system's CoV to -1 indicates a negative relationship between the functions in the system as a whole and a lower likelihood of system success. The CoV is not a guarantee that the system will succeed or fail, nor does it provide any causation for system failure: it is simply the mathematical correlation coefficient and shows whether the functions produce a positively or negatively correlated system (Higgins 2005).

Table 6.4 presented below provides details of the cause-effect co-ordinates from the IM-TIS system, accompanied by the results of the cause-effect co-ordinates for the Tees Valley case study. Column 1 shows the original system and the rank and position of the functions of innovation in the original IM-TIS system and states whether the function is dominant, subordinate or even. Column 2 shows the results of the functions of innovation cause-effect co-ordinates for Tees Valley. The indicators of effectiveness are also presented in this column. The indicators provide details of how the functions of innovation in this case study differ from the results of the original IM-TIS model. The changes in rank and position give an indication of the effectiveness of each function individually and also of the system as a whole.

Table 6.4. Original IM-TIS functions compared with H_2fW IM-TIS(TV), providing indicators of effectiveness

IM-TIS Original System Functions C-E Co-ordinates	H2fW IM-TIS(TV) functions Indicators of Effectiveness (IoE)
Knowledge development and diffusion (15,17) subordinate	c-e coordinates (11,10) - switch from subordinate to dominant function - negative relationship to IM-TIS system - move down cause-effect line reducing % effectiveness of TIS
Influence on the direction of the search (18,14) dominant	c-e coordinates (6,1) - remains dominant function - positive relationship with IM-TIS system - move down cause-effect line significantly reducing % effectiveness of TIS
Entrepreneurial experimentation (19,19) even	c-e coordinates (15,16) - move from even to slightly subordinate function - negative relationship with IM-TIS system - slight move down cause-effect line reducing % effectiveness of TIS
Market formation (17,17) even	c-e coordinates (6,7) - slight change to subordinate function - positive relationship with IM-TIS system - moves down cause-effect line significantly reducing % effectiveness of TIS
Legitimation (18,19) subordinate	c-e coordinates (8,16) - moves to a very subordinate position - negative relationship with IM-TIS system - moves down cause-effect line significantly reducing % effectiveness of TIS
Resource mobilisation (17,19) subordinate	c-e coordinates (7,2) - switch from subordinate to dominant function - negative relationship with the IM-TIS system - moves down the cause-effect line significantly reducing % effectiveness of the system
Creation of positive externalities (18,18) even	c-e coordinates (9,10) - moves to subordinate function - negative relationship with the IM-TIS system - moves down cause-effect line reducing % effectiveness of the system

The overall percentage effectiveness OPE can now be calculated.

$$OPE\% = \frac{total\ value\ of\ \text{H2fW IM} - \text{TIS (TV)}}{total\ value\ of\ IM - TIS} \times 100$$

$$OPE\% = \left(\frac{62}{122}\right) \times 100$$

$$OPE\% = 50.8\%$$

The next step is to calculate the coefficient of vulnerability CoV for Tees Valley. The CoV is represented by r_{xy} (where x=cause and y=effect) in the equation below.

$$r_{xy} = \frac{\Sigma XY - \frac{(\Sigma X)(\Sigma Y)}{n}}{\sqrt{\left[\left(\Sigma X^2 - \frac{(\Sigma X)^2}{n_x}\right)\left(\Sigma Y^2 - \frac{(\Sigma Y)^2}{n_y}\right)\right]}}$$

= 0.8

This coefficient shows a very good relationship between the cause and effect elements of the function. The coefficient suggests a low likelihood of failure in the system. This shows that although the OPE value indicates that the Tees Valley system is operating at half the efficiency desired, the relationship between the cause and effect influences on the functions are positive. This means that the functions are working together and not against each other. This assertion is backed up by the variability of the dominance of each of the functions of innovation shown in Table 6.3.

6.4.2 Key Observations for H_2fW IM-TIS (TV)

Key observations from the case study analysis of Tees Valley are presented in this section. The observations are a product of the initial analysis of the qualitative data that was used to identify existing relationships within the IM-TIS matrix, the cause-effect and ESQ distribution graphs and the Indicators of Effectiveness and Coefficient of Vulnerability. Observations are presented in themes based on the different phases of the case study analyses. Comparisons with the other case studies are made in section 6.8.

1. The evidence from the matrix revealed that there was limited impact from the rest of the system on the *influence of the search* and *resource mobilisation*. This means that these functions are very dominant. The *legitimation* function was shown to be very subordinate to the system. This may mean that legitimation of technologies and the technological innovation system as a whole only occurs after all other activities within other functions are completed and successful. All other subordinate functions were subordinate but not significantly so.
2. From the cause-effect graph (Figure 6.4), the Tees Valley TIS for the sustainable production of hydrogen from waste has shown the TIS to be a moderately interactive system with functions of variable dominance.
3. The ESQ code distribution graph shown in Figure 5.6, which gives details on the number of interactions and relationships that exist in the emerging Tees Valley TIS, displays an inverted graph at Level 3 interactions. Level 3 interactions in the original IM-TIS model are the most frequently occurring interactions and the deficiency of this level of interactions here explains the low level of effectiveness of the overall system at 50.8%.
4. To increase the effectiveness of this TIS it will be necessary to increase the occurrence of the level 3 interactions. This includes **interactions** relating to *influence of the search* and *resource mobilisation*, which currently have little or no influence on the system. Interactions such as, "Increased 'buy in' from businesses, academia and governments promotes policy creation and target setting" and "A firm direction from government towards a particular technology promotes investment and creates jobs" would need to be investigated further. It is notable that there is a lack of level 3 coded interactions relating to *resource mobilisation* in this TIS, reducing its ability to be effective and deliver

sustainable hydrogen from waste. The IM-TIS matrix presented in Figure 6.2 highlights the missing interactions that are shown to relate to the role of the state and academia. This includes relationships such as, *New knowledge shared can promote creation of policies to promote technologies* and *Well communicated science and research can increase confidence in new training opportunities and funding*.

5. The indicators presented in Table 6.4 are designed to provide a more detailed explanation for the low percentage effectiveness of this system. A recurring theme in the indicators is that in every instance the position of each of the functions of innovation within the system has moved compared to the results of the original IM-TIS model. Movement of functions, particularly where the dominance or subordinacy of the function is reversed compared to the orginal IM-TIS has a negative impact on the system as a whole. However, although this may reduce overall system efficiencies as seen in this case study, other results, such as variance of dominance between functions and the CoV also suggest that this system has the potential to be successful.
6. The coefficient of vulnerability determines a positive or negative correlation between the cause and effect elements of the system. In this instance the coefficient is 0.8, indicating the beginning of an emerging system that is unlikely to fail, based on the relationship of the cause and effect of each of the functions within the system.
7. Based on the findings of this case study, the TIS for Tees Valley could be considered a private sector led TIS that broadly meets the requirements of the region's policy framework. However, it has a currently low level of effectiveness that would need to be addressed.

6.5 South Wales Case Study H2fW IM-TIS(SW)

Wales is governed by a devolved administration: the National Assembly for Wales, supported by the Welsh Government. The National Assembly for Wales was formed in 1998 under the Government of Wales Act 1998 (UK Parliament

1998). For statistical purposes, the Welsh Government has split Wales into six areas: Central Wales, North East Wales, North West Wales, Pembrokeshire Haven, South East Wales and Swansea Bay. This second case study region includes both South East Wales and Swansea Bay, within which there are thirteen unitary authorities, each with their own local development plans. The combined population of these areas is approximately 1.5 million (Statistical Bulletin 2010). South Wales has an historical legacy of heavy industries (Data Wales 2013) particularly in the coal and steel industries. In more recent times, developing renewable technologies and sustainable materials have been key elements of the Welsh Government's strategic direction (Welsh Government 2009; 2012).

In 2006, the Welsh Government adopted a legal duty to promote sustainable development. How they propose to meet this duty is laid out in One Wales: One Planet (UK Parliament 2006). Section four of One Wales: One Planet provides details of how the Welsh Government plans to manage sustainable resource use. This is visualised as, "Within the lifetime of a generation we want to see Wales using only its fair share of the earth's resources." The Welsh Government then provides a series of key aims in order to measure successful outcomes toward achieving their vision. These key aims are:

1. We use less energy and are more energy efficient. More of our energy is produced at a community level, close to where it is used, and we are self-sustaining in renewable energy.
2. Every community enjoys better local environments which contribute to health and wellbeing, and local people are involved to promote low carbon, low waste living as part of a One Planet Nation.
3. We have a low carbon transport network, which promotes access rather than mobility so that we can enjoy facilities with much less need for single occupancy car travel.
4. An NHS that leads on low carbon and sustainable development best practice and health services that focus on successful outcomes. (Welsh Government 2009 p. 32)

The fourth key outcome given in the One Wales: One Planet policy document is less relevant to this case study. However, the NHS can also benefit from hydrogen production from waste for energy production and transportation, as described in the first three key outcomes.

In addition, the sustainable development scheme described in One Wales: One Planet, Wales has a series of other policy documents that support the development and use of hydrogen from waste.

The following section provides essential background information about the participating organisations of Glamorgan University (now part of the University of South Wales), the Environment Agency Wales and the Wales Atomotive Forum. Additionally, details of the policy relevant to the sustainable production of hydrogen from waste in the South Wales case study region are provided.

6.5.1 Policy Position

Wales has a devolved administration that operates under the Government of Wales Act 2006. This means that the Welsh Government has responsibility for managing and developing a number of fields and legislative matters including: waste management policies, transport and small energy projects under 50MW (UK Parliament 2006).

The Welsh Government has developed a number of strategies for implementing their legal responsibilities for waste, energy from waste and hydrogen in Wales. The key strategies relevant to this case study are:

1. **Towards Zero Waste – the overarching waste strategy for Wales 2010**. The Welsh Government aims to reduce greenhouse gas emissions through improved waste management. Direct emissions identified are from landfill gas, landfills and the result of transport associated with waste management. Indirect emissions are related to product

manufacture and transport of products, referred to as embedded emissions (Welsh Government 2010 p. 9).

In Wales, energy recovery from waste is officially the penultimate option for waste management. Towards Zero Waste prioritises the “reduce, reuse, recycle“ paradigm. No specific targets or details are given in relation to energy production from waste. However, the strategy refers to eliminating landfill as far as possible, with particular use of anaerobic digestion (Welsh Government 2010 p.58). This, in association with previous statements on reducing direct emissions through improved waste management processes, may lead to more energy and fuels produced from waste management processes. This is not in conflict with the Welsh Government’s plans in this strategy.

2. **Energy Wales: A low carbon transition 2012**: In this strategy, the Welsh Government describe their ambition to unlock Wales’ renewable energy and radically to increase the amount of low carbon energy distributed across Wales (Welsh Government 2012 p.13). They also recognise that, in order to achieve this, infrastructure will need to be updated.

   Hydrogen and energy from waste are not mentioned in this document; however, the use of bio-energy to compensate for the intermittency in supply of some renewable energy technologies is considered (Welsh Government 2012 p.10). This section of the strategy could cover the production of hydrogen from waste for use as a fuel.

3. **Climate Change Strategy for Wales**: In Wales, the Welsh Government has set a target to reduce greenhouse gas emissions by three percent per annum. As part of this strategy, several broad areas are discussed as priorities for reducing emissions that contribute to climate change. These include the following.

- Encouraging smaller scale low carbon energy generation, for example by increasing awareness of the options or by driving demand through public sector investment.
- Supporting businesses in all parts of the supply chain; providing the right skills training and accreditation, and ensuring that there is an enabling planning regime.
- Providing the right environment to encourage low carbon and resource efficient business growth and innovation.
- Working with private and public sector partners to enable the development of larger scale renewable energy generation, and supporting transport investment which encourages a shift to low carbon modes of transport, such as walking and cycling, promotes the use of public transport, and provides advice and support that encourages more sustainable choices.

Hydrogen production from waste could be considered under these broad themes and would be consistent with the requirements of this strategy.

The results of the application of the IM-TIS model are given in section 6.6.

6.5.2 University of South Wales (previously Glamorgan University)

The University of South Wales (USW) is home to the Sustainable Environment Research Centre (SERC) whose laboratories are located on the Glyntaff campus. The group at USW were responsible for the production of the Hydrogen in Wales document (Cherryman *et al.* 2007), which outlined the strategic objectives for the Welsh Government regarding hydrogen production for energy in Wales. SERC specialises in waste treatment and sustainable energy production from waste and biomass. In order to achieve this, considerable investment has been made into the development of laboratories for this research. In particular, hydrogen production from waste through anaerobic digestion and dark fermentation is researched (Glamorgan University 2012).

The University of South Wales has hydrogen research centres at sites in both Baglan and Glyntaff. The Hydrogen Energy Centre was jointly funded by the European Union and Glamorgan University, and is designed to provide a focal point for research, development and demonstration of hydrogen technologies in Wales. This centre specialises in research into fuel cells and their applications, as well as hydrogen production systems.

The University of South Wales is the lead organisation responsible for the European Regional Development Fund-supported CymruH_2Wales Project, which is part of the Low Carbon Research Institute's *Convergence Energy Programme.* The project investigates the role that Wales can play in establishing new hydrogen products, processes and services (University of South Wales 2013). The current phase of the CymruH_2Wales Programme is a £6.3 million project that builds on the previous research conducted by Glamorgan University.

SERC and its partners at the University of South Wales provide the central hub for applied hydrogen research in Wales. They have established connections and collaborative projects working with industry and the Welsh Government. This position of leadership provides them with an opportunity to influence the development of hydrogen policy and strategy within Wales and to guide the Welsh Government, based on the evidence from their research (Cherryman *et al*. 2007) and has made them an ideal participant for the case study undertaken in South Wales.

6.5.3 Environment Agency Wales

The Environment Agency in Wales (EAW) was established as part of the Environment Agency England and Wales. The Environment Agency Wales was replaced by Natural Resource Wales on 1st April 2013 (Natural Resource Wales 2013). It has a responsibility for protecting and improving the environment and contributing to the principles of sustainable development. It is unlikely that the change in organisation would affect the opinions given in the EAW interview. The activities and responsibilities of the organisation remain the same.

EAW was tasked with three core roles and they are:

1. **Environmental regulator** – taking a risk-based approach, targeting their effort to maintain and improve environmental standards and to minimise unnecessary burdens on businesses.
2. **Environmental operator** – a national organisation that operates locally. They aim to work with people and communities across England and Wales to protect and improve the environment in an integrated way and provide a vital incident response capability.
3. **Environmental adviser and champion for the environment** – Compiling and assessing the best available evidence to report on the state of the environment. They provide technical information and advice to national and local governments to support them in policy and decision-making (EAW 2011).

In their Corporate Plan 2011-2015 EAW (2011), it is stated that "Climate change caused by humans, mostly by burning fossil fuels, deforestation and land use change, is one of the greatest threats to people and the environment." In their role as Environmental Regulator in Wales, they are responsible for implementing some of the major regulatory schemes that will contribute to the reduction in greenhouse gas emissions (EAW 2011). This includes the European Union Emissions Trading System, the CRC Energy Efficiency Scheme, and Integrated Pollution Prevention and Control (IPPC).

EAW regulate low-carbon technologies including:

- some renewable technologies (notably biomass, hydropower, ground source heating and cooling and tidal power);
- energy from waste including anaerobic digestion;
- nuclear power (including nuclear waste management); and
- future carbon capture and storage.

EAW's role in relation to regulating energy from waste and working with waste managers to reduce methane emissions from landfill sites is of particular interest in this case study.

As regulator and environmental champion, EAW were ideally placed to contribute to the case study in South Wales as they have connections with many of the organisations testing out new hydrogen and waste technologies. They are responsible for deciding which pilot programmes or major plants are appropriate for the local communities and for issuing permits to these new schemes operating in South Wales.

6.5.4 The Wales Automotive Forum

The Wales Automotive Forum (WAF) is a non-profit company limited by guarantee and supported by the Welsh Government and automotive industry members. WAF describe themselves as having a key role in disseminating information to companies about future trends, whether this is from the vehicle manufacturers, or from the large module suppliers (WAF 2012a).

Information obtained from their website provides details of the four core objectives for WAF, as follows.

- **To act as the voice of the automotive industry in Wales**, performing a lobbying and influencing role with the Welsh Assembly Government and government funded bodies, to ensure that funding and support of the industry are focused, and match the needs of all players in the supply chain. This will cover industry best practice, as well as education and training.
- **To influence the automotive sector strategy** by networking and discussing global and local issue with industry leaders, UK and International Forums, government, and government funded bodies.

- **To forge links and partnerships** with other UK and International automotive forums, promoting the Welsh Capability, to achieve the development of collaboration and co-operative agreements between first, second and third tier suppliers.
- **To provide members with a value for money service** which will enable networking, information dissemination and the use of best practice through organised events and conferences as well as by company visits (WAF 2012a).

In April 2012, two interviews with the Chief Executive of WAF were carried out as part of this research. From the information obtained in these interviews, it was established that WAF are working on a partnership programme with the Welsh Government and automotive industry to 'green' the automotive industry in Wales. This programme of work is called Driving Towards a Greener Wales (WAF 2012) and includes the following objectives:

1. helping companies with greening their products and process,
2. to establish a low carbon vehicle cluster,
3. to establish thematic networks,
4. to create a low carbon vehicle technology park,
5. to contribute to the low carbon skills agenda,
6. to assist with the development of the hydrogen highway in Wales, and
7. to provide intelligence on future vehicles and fuels that will be used to shape future mobility (Williams, date unknown).

WAF's role in aiming to bring together public sector and business to support the development of a hydrogen highway, combined with their desire to support low carbon skills and technologies, made them ideally placed to participate in the South Wales case study.

In 2012 (Welsh Government 2012a), the update on the Climate Change Strategy provided the following details of the current situation regarding the use of alternative fuels in transport in Wales:

- “Additional hydrogen refuelling infrastructure is now in place at the University of Glamorgan’s Glyn Taff campus. The University of Glamorgan’s Renewable Hydrogen Research and Demonstration Centre in Baglan now has a compressed natural gas refueller and a new advanced electrolysis unit is being installed to produce further renewable hydrogen. The University of Glamorgan’s ‘tribrid’ bus is also being upgraded.
- A number of companies have plans to start converting vehicles to run on low carbon fuels.
- At least one of these companies is expected to start vehicle conversions in the next 12 months.”

6.6 Application of IM-TIS to South Wales Case Study H_2fW IM-TIS(SW)

Three in-depth interviews were carried out and analysed in the South Wales region, as described in sections 5.2 and 6.4. Details of the organisations participating in this case study were given in section 5.2.

Figures 6.6 and 6.7 show the relationships and interactions from the IM-TIS model that were found in the analysis of the South Wales case study interviews. Figure 6.6 highlights the relationships that were found and Figure 6.7 provides the co-ordinates for the development of the cause-effect graph given in Figure 6.8.

6.6.1 Results of qualitative data entry into IM-TIS model

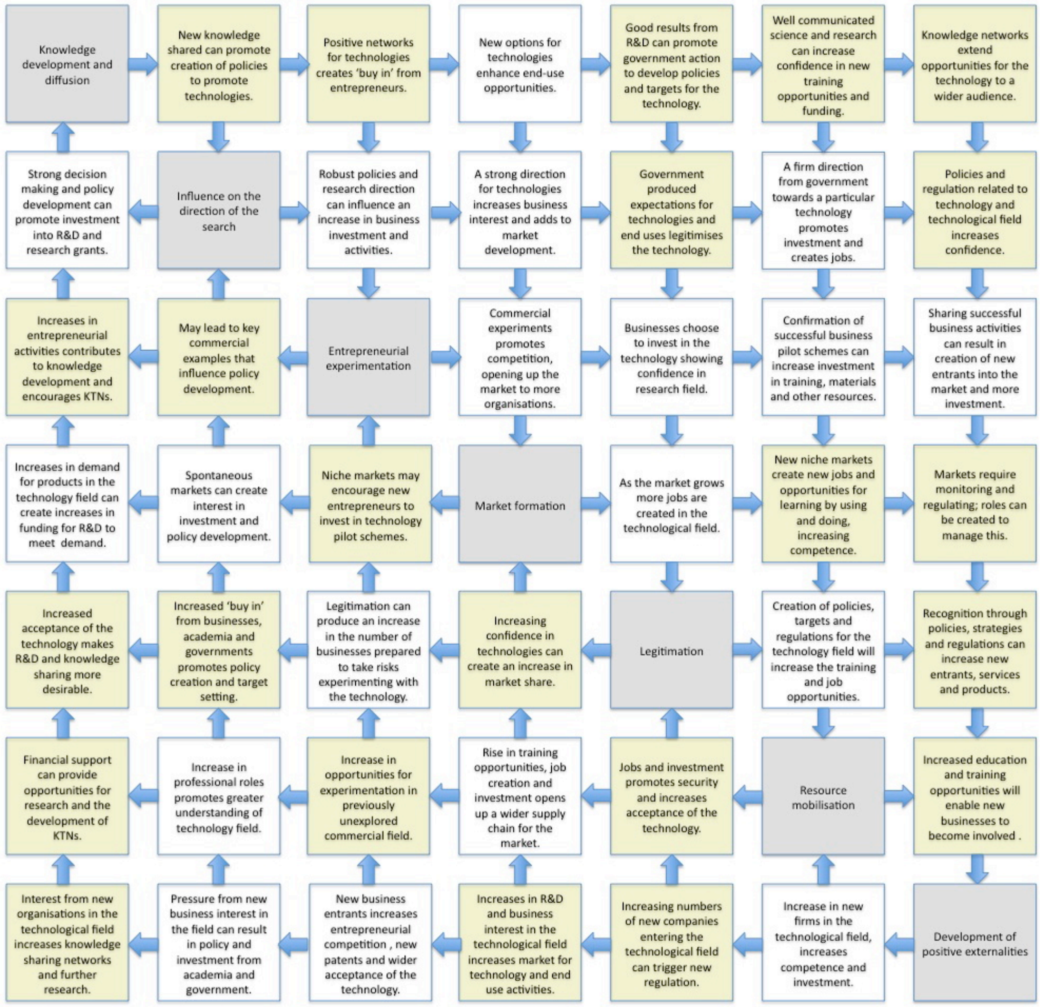


Figure 6.6. Highlighted in yellow are the relationships in the IM-TIS model found from South Wales case study interviews H_2fW IM-TIS(SW).

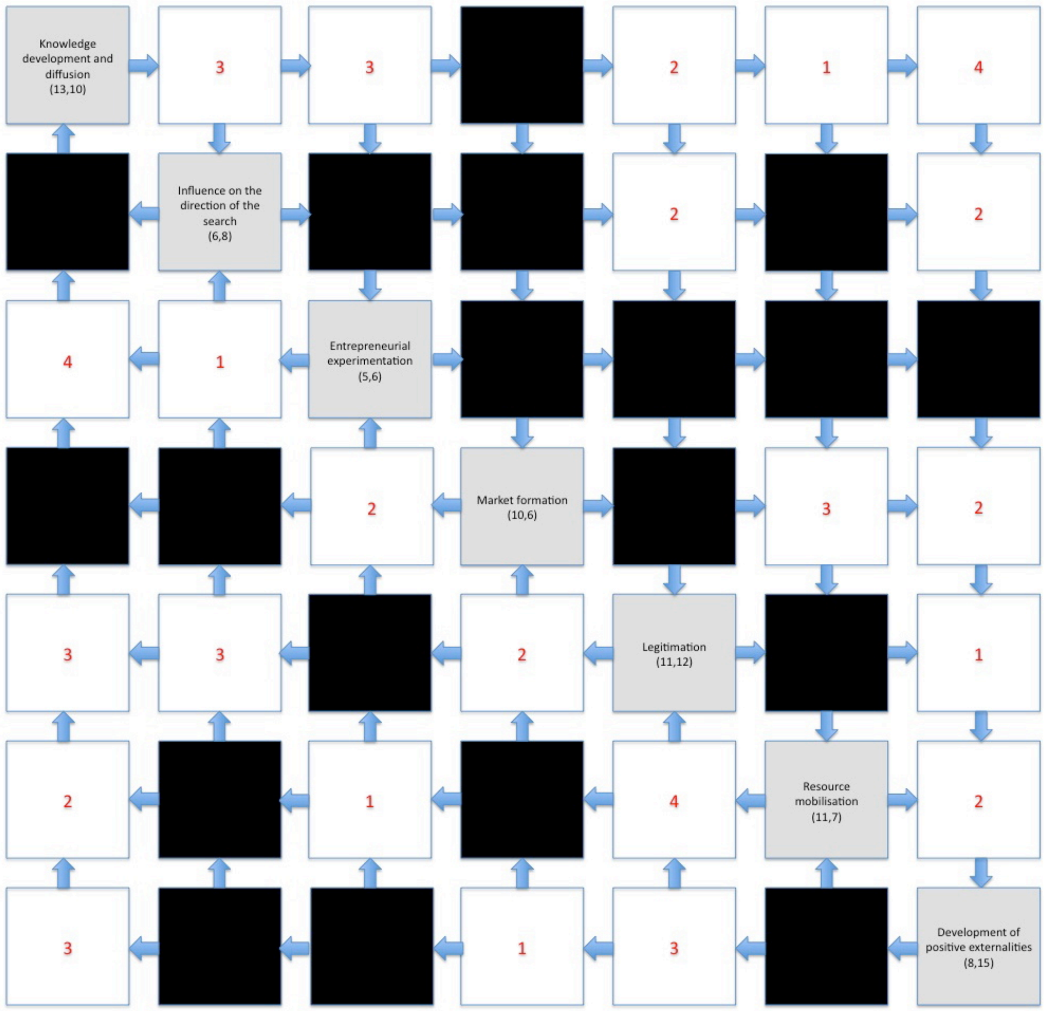


Figure 6.7. Blacking out of the non-existent relationships and interactions in the IM-TIS model, revealing the cause-effect co-ordinates for the functions of innovation in the South Wales case study.

From the results shown in Figure 6.7, the co-ordinates and position of the functions of innovation within the South Wales technological innovation system for the sustainable production of hydrogen from waste can be identified. These are shown visually in Figure 6.8 and described in Table 6.5.

Table 6.5 Functions of innovation and their position in the H_2fW IM-TIS(SW) system

Function of Innovation	Co-ordinates	Rank
1. Knowledge development and diffusion	13,10	Dominant
2. Influence on the direction of the search	6,8	Subordinate
3. Entrepreneurial experimentation	5,6	Subordinate
4. Market Formation	10,6	Dominant
5. Legitimation	11,12	Subordinate
6. Resource mobilisation	11,7	Dominant
7. Creation of positive externalities	8,15	Subordinate

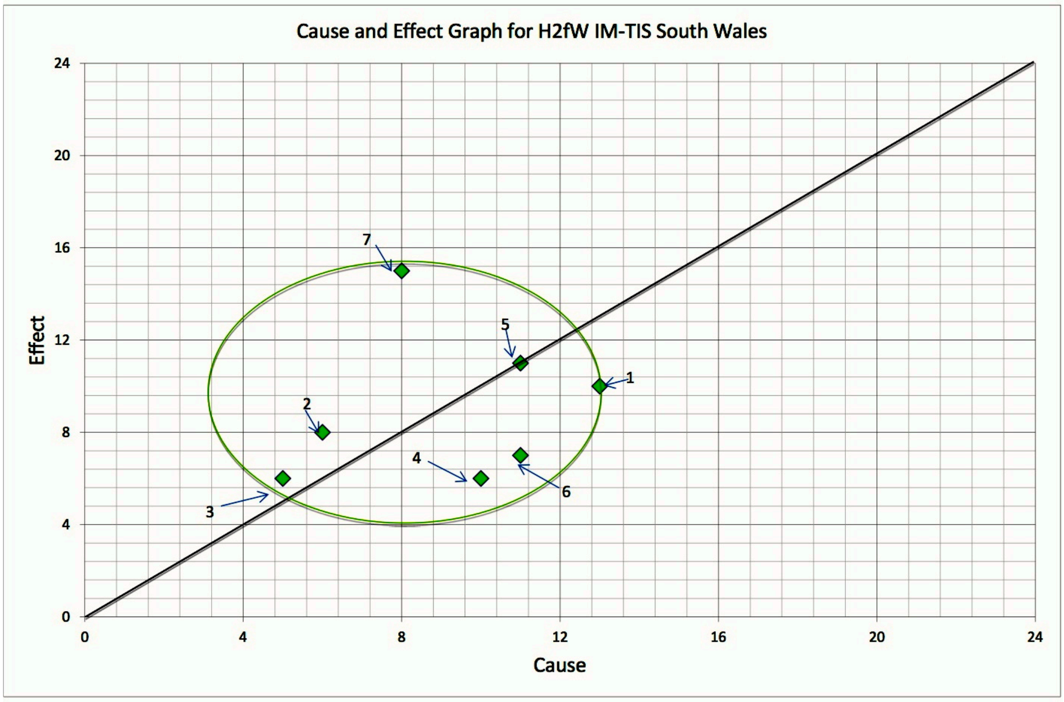


Figure 6.8. Cause-effect graph for H_2fW IM-TIS(SW) functions 1–7.

The cause-effect graph shows a fairly evenly distributed system with even numbers of dominant and subordinate functions. An even set of co-ordinates is where the cause-effect co-ordinates are represented by the same values; for example (15,15) would be an evenly balanced function. The function of *legitimation* presents as slightly subordinate, but close to the cause-effect line meaning that its impact on the system is almost as strong as the system's impact on it.

The system is clustered around the cause-effect line, showing the system to be strongly grouped, with functions of variable dominance and low to moderate interaction. *Market formation* and *Resource mobilisation* have the highest levels of dominance in the system. This means that these functions have the most impact on the system. The most subordinate function in this system is *creation of positive externalities* at co-ordinates (8,15), meaning that this function is strongly impacted on by the system and relies on the actions of the system to influence its role.

The position of the system on the cause-effect line indicates that South Wales has an emerging system and does not yet have strong interactions between the functions that could indicate high overall system effectiveness.

Figure 6.9 shows the distribution of the interactions and relationships that were found in the South Wales case study. The distribution graph shows that more level 3 coded relationships were found, compared to the results of the Tees Valley system, which were shown in Fig 6.5. This follows the distribution graph produced by the original IM-TIS model, meaning that the South Wales technological innovation system for the sustainable production of hydrogen from waste is replicating a similar path to that of the original IM-TIS system.

In the South Wales system, many relationships relating to the role of governance and regulation in the region were apparent, such as, "Government produced expectations for technologies and end uses legitimises the technology" and "Recognition through policies, strategies and regulations can increase new entrants, services and products". From these results, the evidence suggests that this system may be a public sector led technological innovation system. It may be the case that academia and local business are responding to the policies discussed in section 6.5.1. The organisations interviewed for this case study support the idea that it is public sector led as they are all publically funded.

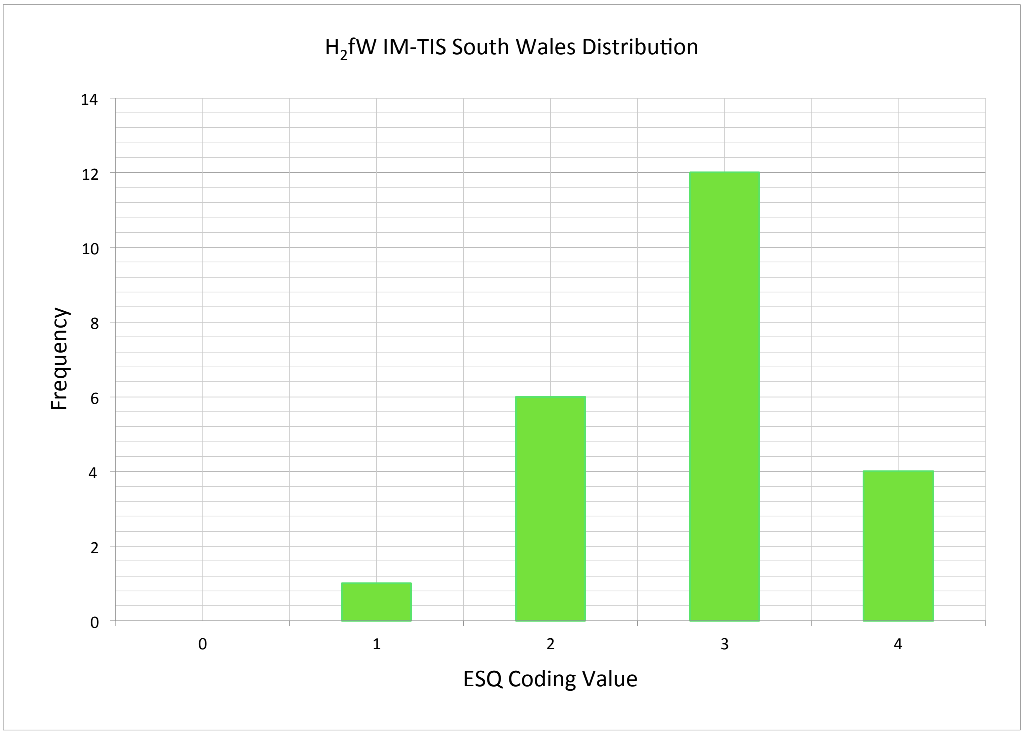


Figure 6.9 shows the distribution of relationships in H_2fW IM-TIS(SW)

To finalise this case study, the indicators of effectiveness, the overall effectiveness and the coefficient of vulnerability were established. Table 6.6 gives details of the indicators of effectiveness in relation to the cause-effect graph and the original IM-TIS model. The indicators provide an idea of the reasons why the overall effectiveness is high or low. The overall effectiveness is then ascertained and finally the coefficient of vulnerability for South Wales is determined.

Table 6.6 provides the original IM-TIS functions of innovation co-ordinates and the new co-ordinates when applied to the South Wales case study. From these, a comparison is made between South Wales and the original outputs, thus producing the indicators shown in the second column.

Table 6.6 Original IM-TIS outputs compared with H_2fW IM-TIS(SW) producing indicators of effectiveness

IM-TIS System Functions (subjects) Maximum	H2fW IM-TIS(SW) functions Indicators of Effectiveness (IoE)
Knowledge development and diffusion (15,17) subordinate	c-e co-ordinates (13,10) - switch from subordinate to dominant function - negative relationship to IM-TIS system - move down cause-effect line reducing % effectiveness of TIS
Influence on the direction of the search (18,14) dominant	c-e co-ordinates (6,8) - switch from dominant to subordinate function - negative relationship to IM-TIS system - move down cause-effect line reducing % effectiveness of TIS
Entrepreneurial experimentation (19,19) even	c-e co-ordinates (5,6) - switch from even to just subordinate - small adjustment compared to IM-TIS system - move down cause-effect line reducing % effectiveness of TIS
Market Formation (17,17) even	c-e co-ordinates (10,6) - switch from even to dominant function - negative relationship to IM-TIS system - move down the cause-effect line reducing % effectiveness of the system
Legitimation (18,19) subordinate	c-e co-ordinates (11,12) - remains at same level of subordinate - no impact on system - move down the cause-effect line reducing % effectiveness of the system
Resource mobilisation (17,19) subordinate	c-e co-ordinates (11,7) - move from subordinate to dominant function - negative relationship to IM-TIS system - move down the cause-effect line reducing % effectiveness of the system
Creation of positive externalities (18,18) even	c-e co-ordinates (8,15) - switch from even to very subordinate - negative relationship to IM-TIS system - move down the cause-effect line reducing % effectiveness of the system

The table shows that in all cases the functions of innovation are operating at a lower level of effectiveness than the original IM-TIS model. The results produced show that the OPE of the South Wales case study is:

$$OPE\% = \frac{total\ value\ of\ H2fW\ IM - TIS\ (SW)}{total\ value\ of\ IM - TIS} \times 100$$

$$OPE\% = \left(\frac{54}{122}\right) \times 100$$

$$= 44.26\%$$

Coefficient of Vulnerability represented by r_{xy} in the equation below:

$$r_{xy} = \frac{\Sigma XY - \frac{(\Sigma X)(\Sigma Y)}{n}}{\sqrt{\left[\left(\Sigma X^2 - \frac{(\Sigma X)^2}{n_x}\right)\left(\Sigma Y^2 - \frac{(\Sigma Y)^2}{n_y}\right)\right]}}$$

= 0.99

In this case study the CoV indicates a highly positive relationship between functions and an effective working system. This was also demonstrated by the results in the ESQ distribution graph and the cause-effect graph. From these results, it could be argued that, although still an emerging system with less than half the effectiveness of the original IM-TIS system, the South Wales TIS for sustainable hydrogen from waste appears to have the potential to be a successful system. This is demonstrated by the close resemblance of the South Wales ESQ and cause-effect graphs to the IM-TIS model and the CoV of 0.99. The production of a high positive in CoV means that with activations of other interactions within the TIS, it could become more effective. These are interactions that are not currently seen in Figure 6.6. In this case, the CoV confirms the results already obtained from the cause-effect graph and the ESQ distribution. The functions of innovation have a positive relationship to each other. This means that, as the co-ordinates of the cause (influence on the system) increase, so does the effect (influence from the system) on the individual functions. This may move towards a system similar to IM-TIS over time.

6.6.2 Key Observations

The overall study of the H2fW IM-TIS (SW) indicated a low level of overall effectiveness, less than half. The ESQ distribution and cause-effect graphs revealed that this emerging TIS is following a similar path to the original IM-TIS system. From this, it seems that this emerging technological innovation system could be successful. Observations from this case study compared to the original model are as follows.

1. There are more subordinate functions in the system, for example, *influence on the direction of the search*, *entrepreneurial experimentation* and *creation of positive externalities* are all subordinate functions, whereas they are dominant in the original IM-TIS. This could mean that the system is relatively more reliant on the actions of the dominant functions and could subsequently become unbalanced.
2. The matrix shown in Figure 6.6 indicates that there are missing relationships and interactions that relate to strong decision making and reinforcement of these interactions through policy and regulation. This can be seen clearly in the blacked out cells in the row that includes the *Influencing the direction of the search* function, showing many absent relationships.
3. The functionality and effectiveness of the system may be improved with the addition of more private and public sector led activities. For example, the creation of professional roles and training programmes would support these elements of the system.
4. The production of a coefficient of vulnerability of 0.99 shows that the relationships between the functions are already very close and that this system is not in a vulnerable state. Raising the system's effectiveness is where future attention will be needed.
5. From the results of the case study and the information obtained from the face-to face interviews, this technological innovation system may be

considered as an emerging public sector led system that meets the requirements of Wales' policy frameworks. This observation is reflected by the organisations who participated in the South Wales case study, all of whom are either public sector bodies, i.e. Environment Agency Wales and the University of South Wales or funded by the Public Sector, as is the case with the Wales Automotive Forum.

6.7 London Case Study H2fW IM-TIS(LN)London

Background detail on the London case study region is covered in this section. Four in-depth case study interviews were carried out in London over the summer of 2012 with members of the following organisations: Imperial College, The Greater London Waste Authority/London Hydrogen Partnership, Croydon Borough Council and Element Energy.

London is the capital city of the United Kingdom and is made up of thirty-two London Boroughs. London has a regional Assembly established under the Greater London Authority Act 1999 (UK Parliament 1999). The Greater London Authority (GLA) serves both The London Assembly and the Mayor. The London Assembly has responsibility for waste, transport and some energy projects carried out in London (London Assembly 2013). As a capital city with a population of approximately seven million, London is the region where several projects relating to hydrogen use and production are being conducted.

The London case study group was designed to include participant organisations from government, academia and private business. London 2012 Olympics and First Bus were also asked to participate; however, these organisations were unable to take part due to other commitments.

The London Hydrogen Partnership (LHP) is a network of interested parties who wish to participate in hydrogen projects in London. They have been involved in a number of projects including the First Bus hydrogen project (TfL 2013) and the

London 2012 hydrogen taxis project (HyTEC 2012). These activities have created a cluster of projects in London and hence made it an ideal region in which to conduct this case study analysis. The study group participants had been involved either directly with the LHP or had been asked to assist with projects in the London case study region. This was the case for Element Energy who have acted as the advisory consultants on a number of projects in London (Element Energy 2012).

The following section provides information on the four organisations that participated in the case study and their roles in relation to the sustainable production of hydrogen from waste. The final part of this section explains the policy position for this regional case study. The results of the application of the IM-TIS methodology for London are given in section 6.8.

6.7.1 London Hydrogen Partnership/ Greater London Waste Authority

The London Hydrogen Partnership (LHP) was created in 2002 by the Greater London Authority to:

- Create dialogue between interested stakeholders
- Offer platforms for funding bids and initiating projects
- Set up forums to prepare and share hydrogen technology research and materials
- Deliver the London Hydrogen Action Plan.

The LHP is a network of stakeholders interested in the development of hydrogen and fuel cells in London (LHP 2012).

In 2010, Boris Johnson, Mayor of London, made this statement:

> *"London has an unrivalled opportunity to benefit from the shift to a low carbon economy. The time for trials and experiments is over; we are putting in place large-scale programmes that can deliver significant CO_2 reductions and billions of pounds in energy savings.*

London has an essential role to play in demonstrating and rolling out new business models that will deliver carbon reductions at scale.

Through our priority programmes, we must stimulate the market and other public organisations to deliver a large proportion of the current target of 60 per cent CO_2 emissions reductions by 2025." (LHP 2010)

The LHP has released the London Hydrogen Action Plan (LHP 2010) that meets the Mayor's vision for the Environment, as well as moving the LHP beyond trials and pilot programmes for hydrogen and fuel cells. The London Hydrogen Action Plan (LHP 2010) addresses three core areas of activity, i.e., strategic hydrogen infrastructure, hydrogen powered vehicles, and stationary fuel cells.

The role of the Greater London Waste Authority is as a member of the LHP with responsibility for delivering the Mayor's ambitions for waste management in London. Consequently, it was judged important to include them in the interviews, with one interviewee representing the role of the GLWA in the LHP.

6.7.2 Croydon Borough Council (London Borough)

Croydon is the southernmost borough of London. It is one of the largest boroughs in London, covering an area of 8662 hectares, with a population of 341,800 (Croydon 2009).

Croydon Borough aims to be *"a place that sets the pace amongst London boroughs in promoting environmental sustainability and where the natural environment forms the arteries and veins of the city"* (Croydon Borough 2010).

As part of this vision, they are running a co-ordinated campaign to include stakeholders across the borough in their ambitious plans. This includes the development of two groups, the Local Strategic Partnership (LSP), and the Environment and Climate Change Partnership (ECCP). The ECCP includes stakeholders, such as Transport for London, The Energy Saving Trust and local schools and businesses (Croydon Borough 2010).

In their Environment and Climate Change Mitigation Action Plan, Croydon Borough state that:

> *"…The ECCP has set a long term target for the borough of a 34% reduction in CO_2 emissions by 2025. This action plan seeks to not only meet this target but also to create opportunities for Croydon in doing so. We aim to make the transition to a low carbon economy and improve energy security by reducing our reliance on fossil fuels. It aims to increase the borough's energy generation capacity using decentralised and renewable energy technologies…" (Croydon Borough 2009)*

In addition to this vision, Croydon has also been involved directly in a project to create hydrogen from waste. Although this project has not been successful in delivering the desired outcomes, Croydon continues to be an advocate of low carbon technologies (Croydon Borough 2012).

This vision of a low carbon future, combined with their recent activities in relation to hydrogen production from waste, means that Croydon Borough Council were judged to be an ideal organisation to participate in the London Case study.

6.7.3 Imperial College

Founded in 1907, Imperial College is a university in London that specialises in Science, Technology and Medicine. Imperial College is consistently rated in the top twenty UK universities and has a strong reputation for industrially related research (Imperial College 2013). In their 2012 Annual Report (Imperial College 2012 p.19), they state that they aim to create the tools to help the UK automotive industry to develop the next generation of lower emission vehicles.

Within the University there are a number of cross-faculty research groups and, for this case study, the Energy Futures Lab group and The Centre for Energy Policy and Technology (ICEPT) participated, being represented by one individual working across both groups. The Energy Futures Lab describes itself as addressing the issue of securing a sustainable energy supply for the future through the support and funding of energy research across Imperial College London (Imperial College 2012).

The Centre for Energy Policy and Technology specialises in the interface between energy technologies and policy development. In the case of technological innovation systems, this is particularly relevant. ICEPT is currently investigating infrastructure, energy vectors and alternative fuels. The role of hydrogen from waste is considered in this research theme and the group are part of the EPSRC-supported SUPERGEN Delivery of Sustainable Hydrogen Consortium, also known as the HDelivery Consortium (Imperial College 2013). This consortium aims to radically improve the way in which hydrogen and hydrogen-based fuels are produced and delivered.

Activities across Imperial College include: biomass and bioenergy studies, renewable energy and low carbon generation, markets policy and system transitions (Imperial College 2013). In relation to low carbon energy futures, Imperial College offer an abundance of experience in these research areas and for the case study investigations.

6.7.4 Element Energy

Element Energy is a private sector consultancy who specialise in energy based activities and low carbon strategies for the future. They have a particular interest in the transport, power generation and buildings sector. Element Energy have produced many consultancy publications: for example, Influences on the Low Carbon Car Market from 2020–2030, for the Low Carbon Vehicle Partnership (Element Energy 2011) and Potential for the application of CCS to UK industry and natural gas power generation, for the CCC (Element Energy 2010). They have consulted on hydrogen projects in London and have significant experience of the activities of the LHP and of other hydrogen-related activities across the UK (Element Energy 2013).

6.7.5 Policy Position

London borough councils may produce and work towards their own environmental and climate change strategies. They are charged with delivering the requirements of the London Assembly. In turn, the London strategy documents deliver EU and UK policy at a regional level.

The key strategy documents delivering London's ambitions for hydrogen from waste are:
Delivering London's Energy Future 2011. The use of hydrogen features in the section of this document that refers to cleaner air for London through the use of low carbon vehicles. Action 5.7 states that the Mayor will continue to support low carbon hydrogen fuel production and its use in London. This will be achieved through the implementation of the London Hydrogen Action Plan with participation and leadership from the London Hydrogen Partnership and industry (London Assembly 2011 pp. 9,17,116). Within this strategy, particular mention is made of promoting waste to energy and taking specific action to catalyse the use of waste-to-energy and hydrogen technologies, as they are said to have significant market potential in London (London Assembly 2011 p. 121).

London's Waste Strategy discusses the possibilities for generating hydrogen or renewable energy from waste through the management of food waste by anaerobic digestion (London Assembly 2011, p. 52). The strategy identifies the following action: The Mayor will work with London's Waste and Recycling Board (LWARB), Transport for London (TfL), and the private sector to develop infrastructure for managing food waste in London. To tackle the issue of food waste, the Mayor has already established the Food to Fuel Alliance. This aims to develop at least five exemplar food waste projects in London that deliver one or more of the following: decentralised renewable heat and power, and renewable transport fuel (bio-fuel or hydrogen) with demonstrable links to hydrogen fuel cells. These exemplar projects should be linked to the Mayor's Capital Growth programme (London Assembly 2011 p. 119).

London is the only case study region where the local policy and strategy makes ***specific*** reference to hydrogen production from waste and identifies actions to move towards this goal. In South Wales, policies are present that could support hydrogen production from waste, but it is not explicit. This makes London an excellent option for analysing the technological innovation system for sustainable hydrogen production from waste.

The following section provides the results of the IM-TIS model application to the real life situation in London at the time of the case study interviews in 2012. A further application of the IM-TIS model analysing policy pathways of the London Case study is given in Chapter 7.

6.8 Application of IM-TIS to the London Case Study H_2fW IM-TIS(LN)

Four case study interviews were carried out in summer 2012. These interviews were in depth and designed to expose the different functions and relationships that can occur in a technological innovation system. This section presents the results of the application of the IM-TIS model to the London case study, as described in section 5.1 and 5.2.

Figure 6.10 shows the results of the analysis of the qualitative in-depth interviews, highlighting which relationships and interactions from the IM-TIS model exist.

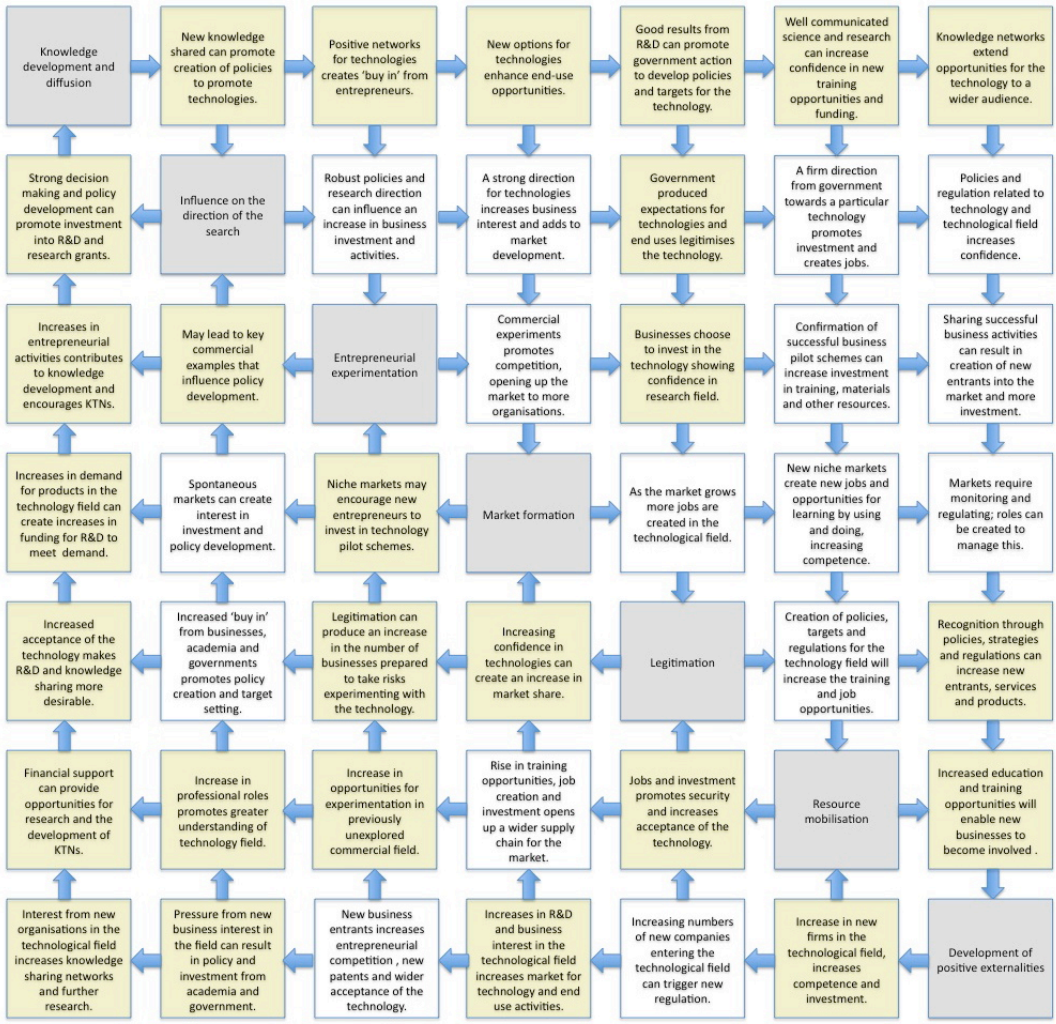


Figure 6.10. Existing interactions in the H_2fW IM-TIS(LN) highlighted in yellow.

From Figure 6.10, it is evident that there are fewer interaction between functions compared to the previous two case studies shown in Figures 6.2 and 6.6. This has a particular impact on *resource mobilisation* where only two interactions are affecting it, one from *knowledge development and diffusion* and one from *development of positive externalities*.

In Figure 6.11, the non-existing interactions are blanked out, revealing that over half (a total of 26/42) of the IM-TIS interactions are present. The co-ordinates for the cause-effect graph can be established from Figure 6.11. The cause-effect graph is presented in Figure 6.12 and the co-ordinates and position of the functions of innovation are given in Table 6.7.

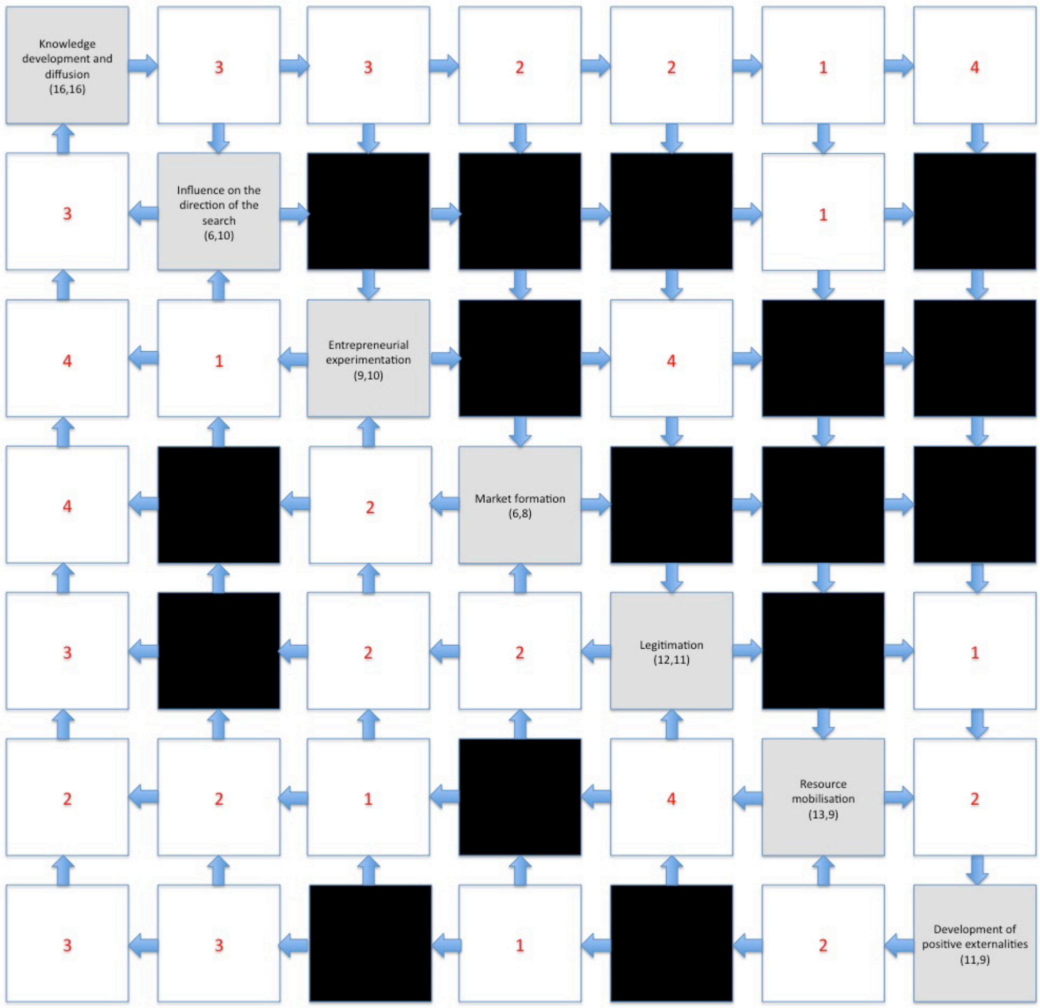


Figure 6.11. Blacking out of the non-existent relationships and interactions in the IM-TIS model, together with the cause-effect co-ordinates for the functions of innovation in the London case study.

Table 6.7. Co-ordinates and positions of the functions of innovation in H2fW IM-TIS(LN)

Function of Innovation	Co-ordinates	Rank
1. Knowledge development and diffusion	16,16	Even (IM-TIS level)
2. Influence on the direction of the search	6,10	Subordinate
3. Entrepreneurial experimentation	9,10	Subordinate
4. Market Formation	6,8	Subordinate
5. Legitimation	12,11	Dominant
6. Resource mobilisation	13,9	Dominant
7. Creation of positive externalities	11,9	Dominant

The table shows a system of dominant and subordinate functions with one even function of *knowledge development and diffusion* that is similar in value to the IM-TIS model position for this function.

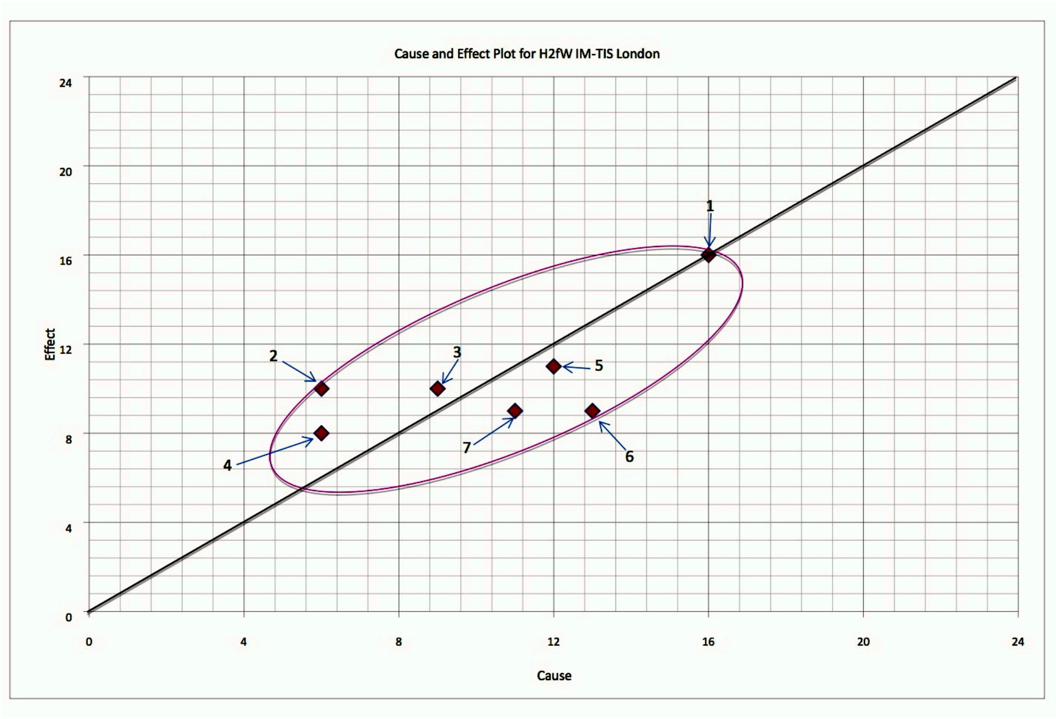


Figure 6.12. Cause-effect graph for H_2fW IM-TIS(LN) functions 1–7

Figure 6.12 reveals the technological innovation system for London to be represented by a stretched cluster of functions close to the cause-effect line. This is a relatively strongly grouped system with lower effectiveness than the IM-TIS system. Functions are distributed evenly between dominant and subordinate creating a balanced system. None of the functions' co-ordinates suggest that the functions in this system are either very dominant or subordinate, noting that the points in Figure 6.12 are all close to the c=e diagonal line.

The function *Influence of the direction of the search* has a C-E difference of 4, with co-ordinates (6,10) this indicates a subordinate function. The close to even balance of the majority of functions in this system suggests that the system could function effectively due to the strong grouping. However, the lack of pressure or leadership from any one or more functions could mean that the system becomes passive and does not achieve desired outcomes.

Figure 6.13 shows the ESQ coded interactions distribution for this case study region. The distribution graph shows a peak in level 3 coded interactions; this is similar to the original IM-TIS system graph. The results from this distribution graph suggest that the technological innovation system for the sustainable production of hydrogen from waste has the potential to be successful as it matures. This is based on the graphical results showing a similar pattern to the original system with peaks and troughs of interactions occurring corresponding to IM-TIS. These data could also denote a public sector led TIS. The lean towards the public sector led system is due to the high frequency of level 3 ESQ coded interactions present in this case study. From the IM-TIS system the interactions coded as level 3 often feature activities and actions associated with the role of government and government organisations.

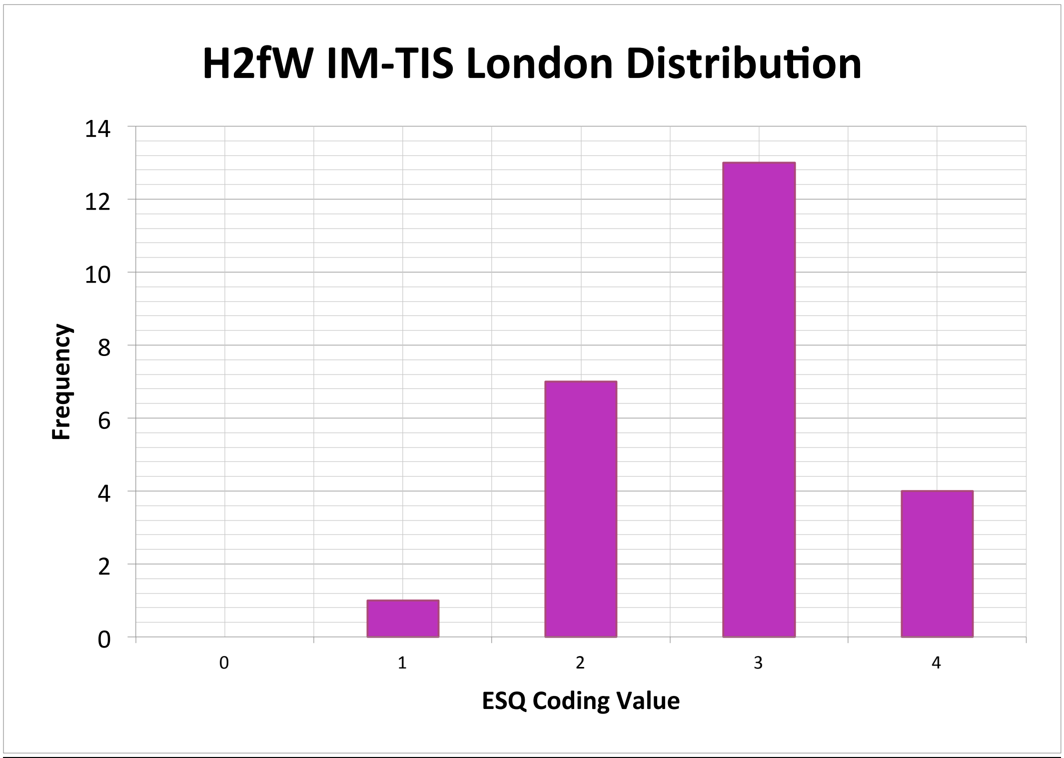


Figure 6.13. ESQ distribution graph for H_2fW IM-TIS(LN).

The indicators of effectiveness are given in Table 6.8, followed by the measures of the overall effectiveness of the technological innovation system and the coefficient of vulnerability. Column 2 of Table 6.8 shows the indicators of effectiveness produced from the London case study region. The cause-effect co-ordinates for the outputs of the original IM-TIS model for each of the functions and their rank are given in Column 1. This allows for easy comparison to be made between the IM-TIS model and the existing system.

Table 6.8. Indicators of effectiveness for the case study H_2fW IM-TIS (LN).

IM-TIS System Functions (subjects) Maximum	H2fW IM-TIS(LN) functions Indicators of Effectiveness (IoE)
Knowledge development and diffusion (15,17) subordinate	c-e co-ordinates (16,16) - switch from subordinate to even function with very similar value to RES-TS - limited impact on the system - no movement on cause-effect line
Influence on the direction of the search (18,14) dominant	c-e co-ordinates (6,10) - switch from dominant to subordinate function - negative relationship to IM-TIS system - move down cause-effect line reducing % effectiveness of TIS
Entrepreneurial experimentation (19,19) even	c-e co-ordinates (9,10) - switch from even to just subordinate - negative relationship to IM-TIS system - move down cause-effect line reducing % effectiveness of TIS
Market Formation (17,17) even	c-e co-ordinates (6,8) - switch from even to subordinate function - negative relationship to RES-TIS system - move down the cause-effect line reducing % effectiveness of the system
Legitimation (18,19) subordinate	c-e co-ordinates (12,11) - switch from subordinate to dominant function - negative impact on system - move down the cause-effect line reducing % effectiveness of the system
Resource mobilisation (17,19) subordinate	c-e co-ordinates (13,9) - move from subordinate to dominant function - negative relationship to IM-TIS system - move down the cause-effect line reducing % effectiveness of the system
Creation of positive externalities (18,18) even	c-e co-ordinates (11,9) - switch from even to dominant function - negative relationship to IM-TIS system - move down the cause-effect line reducing % effectiveness of the system

Table 6.8 shows that, in all functions of innovation, the co-ordinates for their position in the cause-effect graph have moved down the cause=effect line when compared to the original IM-TIS model. This means that the technological innovation system is working at a lower level of effectiveness. The results produced show that the overall effectiveness of the London case study is:

$$OPE\% = \frac{total\ value\ of\ H2fW\ IM - TIS\ (LN)}{total\ value\ of\ IM - TIS} \times 100$$

$$OPE\% = \left(\frac{73}{122}\right) \times 100$$

$$= 59.83\%$$

The coefficient of vulnerability is now calculated for this case study and is represented by r_{xy} in the equation below:

$$r_{xy} = \frac{\Sigma XY - \frac{(\Sigma X)(\Sigma Y)}{n}}{\sqrt{\left[\left(\Sigma X^2 - \frac{(\Sigma X)^2}{n_x}\right)\left(\Sigma Y^2 - \frac{(\Sigma Y)^2}{n_y}\right)\right]}}$$

= 1

The result from this coefficient reflects the results from the cause-effect graph and the ESQ distribution graph, suggesting that the technological innovation system for hydrogen from waste in London is following the pathway defined in the IM-TIS model. In this case study, the CoV confirmed the results from the indicators of effectiveness and the cause-effect graphs. The CoV showed that there is a positive association between the functions of innovation cause and effect on the system. This means that as the cause of a function increases there will be a correlating rise in the effect of that function. This also confirms that the TIS for London is following a pathway that is similar to that of the original IM-TIS model and is supported by the same coefficient value.

6.8.1 Key Observations of H_2fW IM-TIS(LN)

The overall effectiveness of the London case study is 59.83%, which is the highest percentage effectiveness produced from the three case studies, although significantly below that of the original IM-TIS model. Evidence from the matrix revealed an absence of interactions relating to resource mobilisation. Examples of interactions missing for this function are: *Creation of policies, targets and regulations for the technology field will increase the training and job opportunities* and *Confirmation of successful business pilot schemes can increase investment in training, materials and other resources.* The absence of these outcomes from the interactions shown in the matrix suggests that there may be a disconnection between the production of policy and strategy evident in the policy landscape for this region and the buy-in from businesses and local authorities. This could lead to inadequate creation of professional positions and release of finances to support new technologies emerging in this TIS.

The ESQ distribution and cause-effect graphs revealed that this emerging TIS for sustainable production of hydrogen from waste is following a similar path to the original system (IM-TIS). From these results, it seems that this emerging technological innovation system could be successful. Key observations from the London case study are:

1. The system is very closely balanced with even numbers of subordinate and dominant functions—which could lead to a lack of pressure or leadership from any function in the system and increase inefficiencies. A good scenario would be a balance of dominant and subordinate functions, as shown in the original IM-TIS model presented in section 5.1. In the original IM-TIS system, there are functions with greater dominance or subordinance that encourage the system to interact.

2. There may be a need to create additional activities in the TIS to encourage more professional roles, enhancing technology creation, diffusion and commercialisation.
3. The TIS is emerging and following the path of the IM-TIS system and this would need to be monitored to ensure it does not deviate.
4. The production of a coefficient of vulnerability of 1 shows that the relationships between the functions are already very close. It is the overall system's effectiveness where future attention may be needed.

This TIS is well supported by specific policies and actions from the London Assembly. From the results of this case study and the information obtained from the face-to face interviews, the TIS may be considered as an emerging public sector led system that broadly meets the requirements of London's policy frameworks.

6.9 Comparison of case study results

Three case studies of the UK regions, Tees Valley, South Wales and London were completed. In each case study section presented earlier in this Chapter, the case study results have been compared to the original IM-TIS presented in the Methodology Chapter. In this section, results from the cause-effect and ESQ distribution graphs are compared, along with the indicators of effectiveness and coefficients of vulnerability. The comparison aims to show similarities and differences between the technological innovation systems in each region and to identify what level of impact the different functions have in each region.

6.9.1 Cause–Effect Graphs

Figure 6.14 shows the different groupings for the technological innovation systems in each of the case study regions. The graph shows that in shape, South Wales (green) resembles the original system with somewhat more distributed functions of innovation. The systems in Tees Valley (blue) and London (purple) are similar in shape. However, Tees Valley shows two functions that are very dominant and low on the cause-effect line, which could suggest that they are not efficient functions. The rest of the functions in both Tees Valley and London are closer to the cause-effect line, but not at the same strength of efficiency as those in the IM-TIS model. However, analysis of the Tees Valley and London case studies indicates that similar grouping shapes do not necessarily mean that the TIS are similar. This can be seen more clearly in Figure 6.15 where the ESQ coding graph is presented.

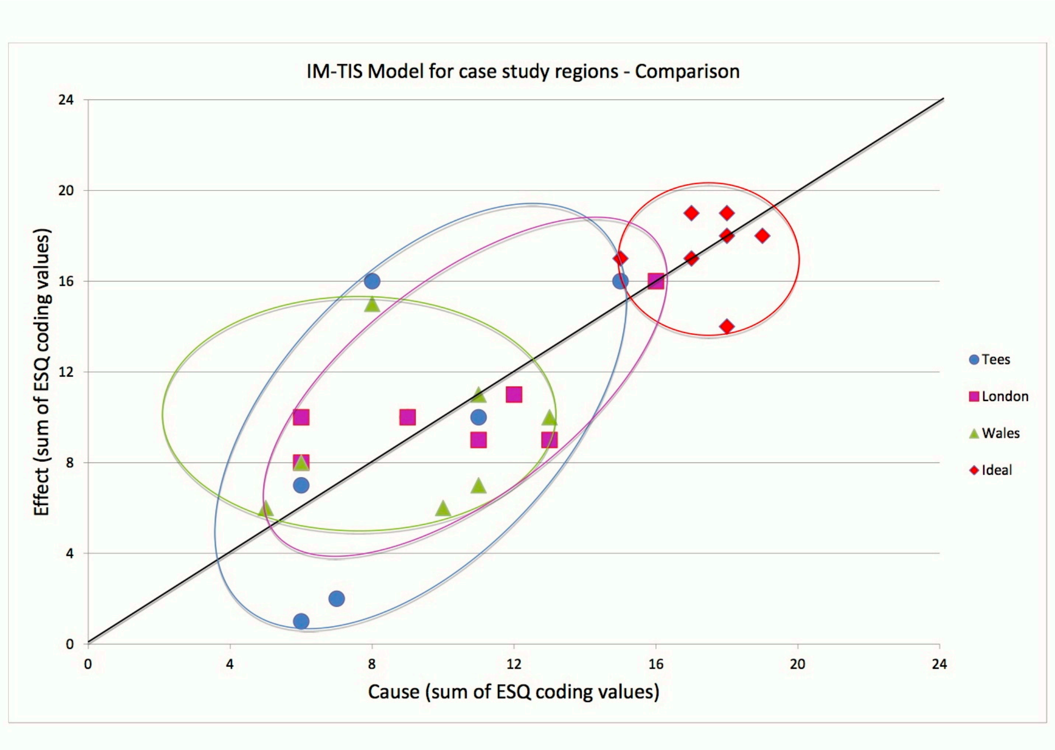


Figure 6.14. Comparative cause-effect graph for all regions and the original IM-TIS.

6.9.2 ESQ Distribution graphs

Here, the ESQ distribution graphs are shown to compare the frequencies of the different level matrix interactions for each case study region. Existence of interactions was established from the in-depth interviews carried out for the case studies.

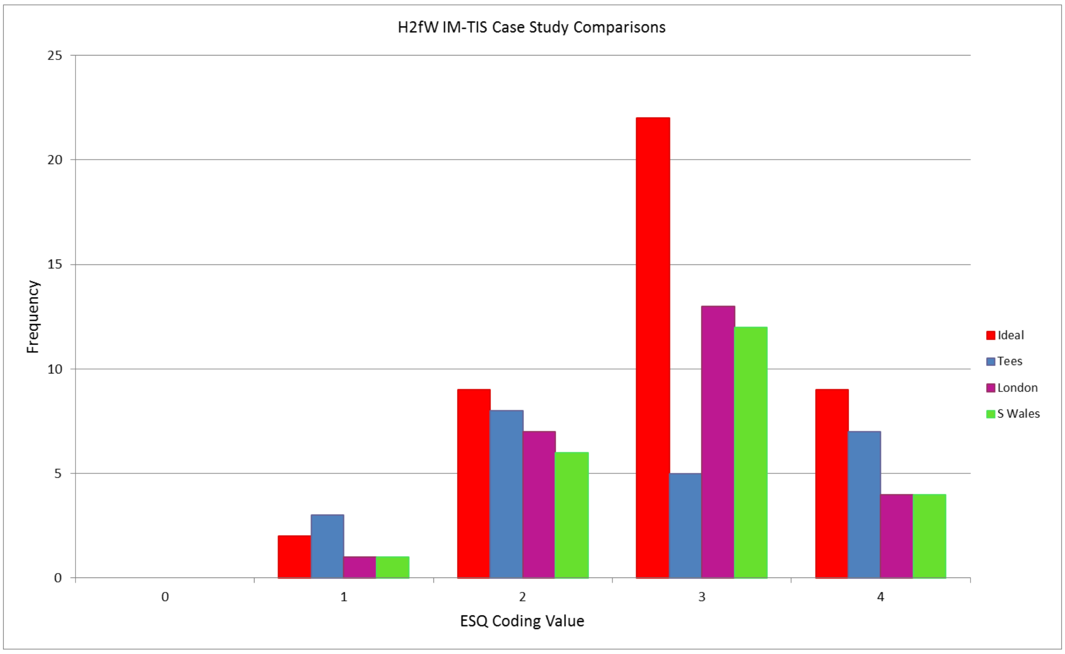


Figure 6.15 ESQ coding comparison distribution graph for all case study regions and the IM-TIS model.

Based on the percentage effectiveness for all case studies, the emerging technological innovation systems all have potential. In the case of South Wales and London, the routes displayed in the ESQ distribution graph reflect the results of the original IM-TIS model shown in section 5.1, although at lower efficiencies, i.e. fewer relationships are in existence in the model. This is displayed in Figure 6.2. For Tees Valley, potential is demonstrated through percentage effectiveness and private enterprise expressed in interviews and highlighted in the matrix. Figure 6.7 shows the absence of interactions in the South Wales case and that South Wales is operating at a lower efficiency than London. This result is reflected in the overall efficiencies calculated at 44.26% and 59.83% respectively. The percentage effectiveness of the London case study was significantly higher than Tees Valley and South Wales due to the supporting policies at the London Assembly. Evidence for this support was elucidated in the interviews from Croydon Borough, the London Hydrogen Partnership and Imperial College (Croydon Borough 2012; LHP 2012; Imperial College 2012).

By comparing the ESQ distribution graphs, the differences described in the individual case studies between Tees Valley and South Wales and London are clarified. The Tees Valley distribution bar (blue) presents a lower number of level 3 interactions compared with the other two case studies and the results of the original IM-TIS model. This is distinctly different from those of South Wales and London that follow the original IM-TIS path. The level 3 interactions are those that are expected to occur in a technological innovation system in order to make it work efficiently. They are not critical interactions (Level 4 interactions are considered critical), but interactions that would be expected to assist successful delivery in all functions of innovation.

Many Level 3 interactions relate to the work of the government in the original innovation system model presented by IM-TIS. For example, the following interactions are ranked at level 3 and missing from the Tees Valley case study: *New knowledge shared can promote creation of policies to promote technologies; Creation of policies, targets and regulations for the technology field will increase the training and job opportunities*; and *A firm direction from government towards a particular technology promotes investment and creates jobs*. From this evidence, it seems that this case study is led by the private sector and that these level 3 interactions occurring in South Wales and London suggest public sector led innovation systems.

6.9.3 Functions of Innovation co-ordinates and ranks and efficiencies

In this section, the position of the individual functions of innovation within each case study is compared and considered. This is based on the cause-effect co-ordinates. In many cases, the dominance and subordinance of the functions is reversed compared to the results of the original model, although the difference may not be large. From the previous results, seen in the cause-effect graph and ESQ distribution graphs, the change in position of functions and different occurrence of interactions does not seem to automatically reduce efficiencies. It is likely that the overall efficiencies of the system are not automatically influenced by the dominance or subordinance of the function, but by the overall number of interactions in existence within a case study region. It is the existence of the interactions that determines the efficiency, not the rank of the function. In all case studies, the efficiency is less than the results seen in the original IM-TIS model. This is a direct result of the lack of interactions in each case study. If they were all to exist, the case study regions would mirror the original IM-TIS model.

Table 6.9 lists comparative data for all the case study regions against the IM-TIS model. This table shows the rank and position of each of the functions of innovation in each regional case study. The results show that the Tees Valley has different indicators to the South Wales and London case studies, reinforcing the suggestion that these regions support different types of TIS. As noted in section 6.6, the results of the TIS in South Wales were a reflection of the types of organisations taking part in hydrogen production from waste activities in the region. This is also the case in Tees Valley, where all participants with an interest in hydrogen in the region are private enterprises.

Table 6.9. Cause-effect co-ordinates for functions of innovation in all case study regions.

IM-TIS Original System Functions (subjects)	H2fW IM-TIS(TV) functions Indicators of Effectiveness (IoE)	H2fW IM-TIS(SW) functions Indicators of Effectiveness (IoE)	H2fW IM-TIS(LN) functions Indicators of Effectiveness (IoE)
Knowledge development and diffusion (15,17) subordinate	(11,10) Switch from subordinate to dominant function. Negative relationship to original system. Move down cause-effect line reducing % effectiveness of TIS	(13,10) Switch from subordinate to dominant function. Negative relationship to original system. Move down cause-effect line reducing % effectiveness of TIS.	(16,16) Switch from subordinate to even function with very similar value to IM-TIS. Limited impact on the system. No movement on cause-effect line.
Influence on the direction of the search (18,14) dominant	(6,1) Remains dominant function. Positive relationship with original system. Move down cause-effect line significantly reducing % effectiveness of TIS.	(6,8) Switch from dominant to subordinate function. Negative relationship to original system. Move down cause-effect line reducing % effectiveness of TIS.	(6,10) Switch from dominant to subordinate function. negative relationship to original system. Move down cause-effect line reducing % effectiveness of TIS.
Entrepreneurial experimentation (19,19) even	(15,16) Move from even to slightly subordinate function. Negative relationship with system. Slight move down cause-effect line reducing % effectiveness of TIS.	(5,6) Switch from even to just subordinate. Small adjustment compared to original system. Move down cause-effect line reducing % effectiveness of TIS.	(9,10) Switch from even to just subordinate. Negative relationship to original system. Move down cause-effect line reducing % effectiveness of TIS.
Market Formation (17,17) even	(6,7) Slight change to subordinate function. Positive relationship with system. Moves down cause-effect line significantly reducing % effectiveness of TIS.	(10,6) Switch from even to dominant function. Negative relationship to original system. Move down the cause-effect line reducing % effectiveness of the system.	(6,8) Switch from even to subordinate function. Negative relationship to original system. Move down the cause-effect line reducing % effectiveness of the system.
Legitimation (18,19) subordinate	(8,16) Becomes a very subordinate function. Negative relationship with system. Moves down cause-effect line significantly reducing % effectiveness of TIS.	(11,12) Remains at same level of subordinates. No impact on system. Move down the cause-effect line reducing % effectiveness of the system.	(12,11) Switch from subordinate to dominant function. Negative impact on system. Move down the cause-effect line reducing % effectiveness of the system.

IM-TIS Original System Functions (subjects)	H2fW IM-TIS(TV) functions Indicators of Effectiveness (IoE)	H2fW IM-TIS(SW) functions Indicators of Effectiveness (IoE)	H2fW IM-TIS(LN) functions Indicators of Effectiveness (IoE)
Resource mobilisation (17,19) subordinate	(7,2) Switch from subordinate to dominant function. Negative relationship with the original system. Moves down the cause-effect line significantly reducing effectiveness of the system.	(11,7) Move from subordinate to dominant function. Negative relationship to original system. Move down the cause-effect line reducing % effectiveness of the system.	(13,9) Move from subordinate to dominant function. Negative relationship to original system. Move down the cause-effect line reducing % effectiveness of the system.
Creation of positive externalities (18,18) even	(9,10) Moves to subordinate function. Negative relationship with the original system. Moves down cause-effect line reducing % effectiveness of the system.	(8,15) Switch from even to very subordinate. Negative relationship to original system. Move down the cause-effect line reducing % effectiveness of the system.	(11,9) Switch from even to dominant function. Negative relationship to original system. Move down the cause-effect line reducing % effectiveness of the system.

Each function of innovation is now considered separately.

1. **Knowledge development and diffusion** – in all cases, this function changes its position relative to the results of the original model, moving away from subordinate to either a dominant or even function. This indicates that the original IM-TIS model does not reflect the nature of activities in 'real' situations and this function is having a greater impact on the system as a whole than considered in the original IM-TIS system. It may also be argued that perhaps knowledge development and diffusion is easier to achieve than other functions and could be considered an indicator of an immature system. The indicators given in Table 6.9 also suggest that this change in function position may have a negative effect on the system. However, results from the ESQ distribution graph given in Figure 6.15 contests this, particularly in the case of South Wales and London. In all cases, the effectiveness of this function within the system is reduced and may be explained by the emerging nature of these technological innovation systems for hydrogen production from waste.

2. **Influence on the direction of the search** – There is a contrast in this function between South Wales and London and the system presented for Tees Valley. Tees Valley maintains the dominant position for this function, whereas South Wales and London exhibit a switch to subordinacy. This result is echoed by the ESQ distribution graphs showing similar pathways for South Wales and London. In all three case studies, this function descended the cause=effect line, reducing the effectiveness of this function. The IM-TIS model presents this function at co-ordinates of (18,14) and, in the regional case studies, it appears at (6,1), (6, 8), (6,10) for Tees Valley, South Wales and London respectively.

3. **Entrepreneurial Experimentation** – In all three case studies, this function shifts from even, i.e. equal co-ordinates, where the effect on the system from the function and the effect from the system on the function are considered equal, to a subordinate function where the system has more influence on the function. A shift in either direction would be likely as a system operating an even function would not be commonplace in "real life" scenarios. Entrepreneurial Experimentation operates most closely to the original system in the case study carried out for Tees Valley and reinforces the idea of a private sector led innovation system where businesses are experimenting with technologies to enhance their commercial viability. The use of experimentation by private business in Tees Valley was a key discussion point in the in-depth interviews (SITA 2012; Air Products 2012). In South Wales, this function is particularly weak compared to other regions and would require further promotion to increase the overall effectiveness of the system.

4. **Market formation** – There is no pattern evident for the market formation function. As an even function, the same difficulties presented for Entrepreneurial experimentation would apply. In all cases, this function has moved down the cause=effect line, reducing the effectiveness of the

function. However, the TIS presented for these case studies are immature and does not support any commercialised projects. This indicates an obstacle for the development of the function within the system, due to the need for actual hydrogen production to occur and for hydrogen to be available for sale. Such developments would, in turn, increase supply chain development and experiences and increase knowledge of the availability of sustainably produced hydrogen in the regions. *Market Formation* presented as most effective in the South Wales case study. This may be a consequence of the pilot projects being carried out by Glamorgan University (Glamorgan Interview 2012).

5. **Legitimation** – This function has similar levels of effectiveness across all case study regions, which are lower than the results from the original model. In Tees Valley and London, legitimation switches from a subordinate to a dominant function compared to the original model, and in South Wales it remains a dominant function. No case study region shows legitimation to be either very subordinate or very dominant and the cause-effect co-ordinates are close in value. This may mean that legitimation is a general function occurring without specific interventions in syncronisation with the emerging TIS.

6. **Resource mobilisation** – In all three case studies, this function switched from subordinate to dominant, suggesting that it is an important function with an impact on the system as a whole that influences success. It is the only function that has shown a complete shift from one position in the conceptual model to another in 'real' case study investigations. In this case, the position of this function in the conceptual model does not reflect 'real' situations. This means that the ESQ levels applied to the relationships identified in the original IM-TIS were incorrect and need to be adjusted for future applications of the original IM-TIS model. The importance of financial and human resource mobilisation was expressed

in all the in-depth interviews. All the case studies showed this function as reduced in effectiveness.

7. **Creation of positive externalities** – In Bergek *et al.* (2008), this function was not considered to be worthy of further investigation, based on the needs of the Swedish innovation programme as described in section 2.4. Contrastingly, in these UK case studies this function has performed well, particularly in South Wales. Defined as an even function in the IM-TIS model, the creation of positive externalities has switched to both a subordinate and a dominant function. In the case of South Wales, it is presenting as very subordinate. It could be considered that this is the most probable position for this function because externalities are more achievable following demonstrable outcomes from the other functions. However, it may also be argued that to motivate all the functions, early creation of positive externalities would be preferable.

6.9.4 Coefficients of Vulnerability

The coefficients of vulnerability produced in the case study regions for Tees Valley, South Wales and London are 0.8, 0.99 and 1 respectively. This shows that in all cases the functions of innovation in each case study have a positive relationship with each other. South Wales and London produced coefficients most closely aligned to the original IM-TIS system. The production of similar coefficients is a reflection of the pattern presented by South Wales and London in the ESQ distribution graph in Figure 6.15. It is important to note that the application of the CoV as part of the IM-TIS model has been used to confirm the results of cause-effect graphs and indicators of effectiveness. The CoV has shown that the cause-effect elements of each function are working for and not against each other. This is through the correlation of cause-effect co-ordinates for the functions of innovation.

6.10 Study Limitations

These case studies have analysed the technological innovation system for the sustainable production of hydrogen from waste in each of the case study regions. The interviews carried out to support the interaction matrix development can only be considered to represent the organisation's view at that point in time. The interviews discussed considerations of future expectations for hydrogen from waste, but could not take into account advancements in knowledge and experience of the interviewee over time. In order to understand more clearly how the technological innovation system may change and which interactions emerge over time, the case study investigations would need to be carried out again at specified intervals.

The IM-TIS model is designed to identify relationships and interactions that occur between the functions of innovation in the system. As such, it does not consider in detail the overall drivers for the further development of the innovation system. This may need further investigation to improve the IM-TIS model.

6.11 Concluding Comments

In this chapter, the IM-TIS model has been applied to three case study regions. An adaptation of the Rock Engineering Solutions (RES) model IM-TIS combines an interaction matrix with the conceptual framework of functions of innovation. In previous studies, the RES model has not been combined in this way and has not been applied to case studies in this manner. In this novel application of RES, an original pre-designed system with existing outputs has been proposed for comparison to the case studies. Previous studies have evolved from existing systems, not pre-designed systems. RES has been used to evaluate existing relationships and was not been designed to help guide a system towards a desired future. From this viewpoint, the case studies have been examined, based on the system identifying which interactions existed at the time of the analyses. The IM-TIS model can offer analysis of a number of interactions that are required in each region in order to move each system closer to the original technological innovation system. The activation of these interactions will occur over time and, to understand the future development of the system, the case studies would need to be repeated at specified intervals. It is the pre-design of the model that allows for the comparison of the case studies, offering a novel perspective on the technological innovation system for hydrogen from waste in each region.

In this chapter, the study groups involved in the three case studies have been described. The IM-TIS model has been applied to the case study regions using the data obtained from the in-depth interviews. From the case studies, it has been possible to establish the existence of two types of technological innovation system relating to sustainable production of hydrogen from waste in the UK. These are public and private sector led systems.

The findings have helped to establish how different actors, organisations and institutions influence the functions of innovation and how these relate to the functions identified in the IM-TIS model.

The differences between the *public* and *private* sector led systems relate to the interactions and relationships present in the case study systems. The *public sector* systems are characterised by the existence of a larger number of interactions that include elements of policy or public funding. In contrast, the *private sector* system is characterised by a larger number of business and enterprise led relationships. This information about the nature of the emerging TIS could support the development of policies and roadmaps through the application of targets and actions to address the missing interactions. In turn, the specific identification of these interactions would increase the overall system effectiveness in each of the regions.

Results from the cause-effect positions of the different functions in the three case studies have produced evidence that the *resource mobilisation* function may be the key function in 'real' situations. In addition to this, the role of *the creation of positive externalities* could be far more important than considered in earlier literature on the functions of innovation used in these case study investigations. From these results, it may be necessary to reconsider the ESQ coding applied to the original IM-TIS model. This would give these functions the rank and position the case studies have shown they require.

In this chapter, the results have also addressed the sub-research question of: *What does the comparison (Aim 2) between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?* Reflecting on the case studies and the participants, the sustainable production of hydrogen from waste sector could be considered as having a limited number of active organisations within it. This means that the TIS associated with this field are likely to be immature and emerging. As more businesses, academics and public sector organisations become involved in this field, the TIS should mature and this would become evident in a reapplication of the IM-TIS model to the case studies.

The results show that, in both South Wales and London, the conceptual IM-TIS model developed for the analysis of the case study regions does reflect 'real situations' In these regions it is has been found that the cause-effect co-ordinates may not accurately place functions within the system. This would not be the case if all interactions identified in the original IM-TIS were present. This may be resolved for future uses by adjusting the ESQ levels applied to each interaction in order to position the functions more accurately.

In the case of Tees Valley, the results of the application of IM-TIS showed that Tees Valley is a private sector led TIS. The closer resemblance of London and South Wales to the original IM-TIS suggests that the model developed for these case studies has a public sector bias and is itself a public sector led model. Bias in a TIS may not necessarily be negative, particularly if the government wants to affect some particular change. However, if the goal of the TIS is to create sustainable businesses producing particular technologies and infrastructure, then public sector bias may prevent this from occurring. This would be due to government funded interventions not automatically create sustainable businesses.

The results from these case studies suggest that should government, business and academia continue to show interest in technologies for the production of hydrogen from waste, there could be a place for hydrogen from waste in future energy systems. In South Wales and London, the TIS are following the pattern of the IM-TIS model towards a successful innovation system for hydrogen from waste. A successful system would suggest commercialisation of these technologies and greater acceptance and legitimation of these technologies within an incumbent energy and waste system. The results from Tees Valley show that, where there is less input from government and state funded organisations, businesses are trying to create a market for hydrogen from waste. Businesses seem to have identified the potential for hydrogen production and energy production from waste (Air Products 2012; Impetus waste 2012; SITA UK 2012). However, there are no commercial hydrogen from waste plants operating in Tees Valley.

In this Chapter, case study analyses have been used to establish the situation within three UK regions that relate to the technological innovation system for hydrogen production from waste. A conceptual model has been applied to "real life" situations and the results obtained indicate that, in the case study regions for South Wales and London, the conceptual model does reflect the 'real' situation. The results have shown that the conceptual model itself has some public sector bias and that there is a need to revisit the ESQ distribution in the original model to represent business and enterprise more accurately. The case studies have provided some insight into the behaviour of different key actors within each case study region. Thus, these case studies have provided further understanding of the role that hydrogen from waste might play in a future energy system, thereby helping to address the overarching research question.

In the following chapter, the use of the IM-TIS model for policy and road map development is described, with specific reference to a number of UK and devolved administration policies and strategies. This is shown using a worked example based on the policies relating to the London case study region. The use of pathway management in the IM-TIS system is also covered; this was not part of the model application in the case studies.

6.12 References

Air Products 2011. Hydrogen Energy Station. Renewable Hydrogen Fuelling Infrastructure 2011. Accessed online March 2013. www.airproducts.com

Air Products 2012. Personal Communication. (Interview) June 2012

Air Products 2012a. We are Air Products. Annual Review 2012. Accessed online August 2013 http://www.airproducts.com/company/company-overview.aspx

Air Products 2012b. Annual Report 2012. Accessed online August 2013 http://investors.airproducts.com/phoenix.zhtml?c=92444&p=irol-reportsannual

Bergek A., Jacobsson S., Carlsson B., Lindmark S., Rickne A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (2008) 407-429

Chatham House 2012. The circular economy. Accessed Online 24/04/2013 http://www.chathamhouse.org/research/eedp/current-projects/circular-economy

Cherryman S.J., Maddy J., Hawkes F.R., Hawkes D.L., Dinsdale R.M., Guwy A.J., Premier G.C. 2007. Hydrogen and Wales. A Vision of the Hydrogen Economy in Wales: Placing Wales in a Position to Take Full Advantage of the Hydrogen Economy. Report Number3 ERDF part funded project entitled: A Sustainable Energy Supply for Wales: Towards the Hydrogen Economy. http://www.h2wales.org.uk/documents/4.html

Croydon Borough 2009. Croydon Climate Change Mitigation Action Plan. Croydon Climate Change and Environment Partnership. http://www.croydon.gov.uk/contents/departments/environment/pdf/ccmaplan.pdf

Croydon Borough 2010. We are Croydon. This is our Vision. 2010. Croydon http://www.croydon.gov.uk/contents/departments/community/pdf/CommStrat1015

Croydon Borough 2012. Personal Communication. (Interview) June 2012.

Data Wales 2013. An industrialisation of the South Wales Valleys. Accessed Online 24/04/2013 http://www.data-wales.co.uk/valley1.htm

DECC 2011. UK Renewable Energy Roadmap. Department of Energy and Climate Change. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48128/2167-uk-renewable-energy-roadmap.pdf

DECC 2012. DECC Science and Innovation Strategy 2012. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48335/5107-decc-science-innovation-strategy-2012.pdf

DEFRA 2000. Waste Strategy England and Wales. Department for Environment, Transport and the Regions.

DEFRA 2007. Waste Strategy for England 2007. Department for Environment Food and Rural Affairs. http://www.wasteconnect.co.uk/downloads%5CWasteStrategy_01072009100355.pdf

DEFRA 2011a. Anaerobic Digestion Strategy and Plan 2011. A commitment to increasing energy from waste through anaerobic digestion. Department of Energy and Climate Change; Department for Environment Food and Rural Affairs Publication.

DEFRA 2011b Waste Policy in England. Government Review and Action Plan 2011. Department for Environment, Food and Rural Affairs. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69402/pb13542-action-plan-.pdf

Element Energy 2012. Personal Communication. (Interview) July 2012.

Element Energy 2010 Potential for the application of CCS to UK industry and natural gas power generation, for the CCC. Accessed online March 2013 http://www.element-energy.co.uk/publications/

Element Energy 2011. Influences on the low carbon car market from 2020–2030, for the Low Carbon Vehicle Partnership. Accessed online March 2013. http://www.element-energy.co.uk/publications/

Element Energy 2013. Element Energy Website – About us information and publications. http://www.element-energy.co.uk

European Parliament 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

Glamorgan University 2012. Personal Communication. (Interview) June 2012.

Higgins J. Excerpted from The Radical Statistician by Jim Higgins, Ed.D. Copyright 2005 Management Advantage.

HyTEC 2012. Hydrogen fuel cell electric taxis drive Olympic VIPs 2500 miles. HyTEC website accessed online August 2013. http://hy-tec.eu/2012/uncategorized/hydrogen-fuel-cell-electric-taxis-drive-olympic-vips-2500-miles

Imperial 2012. Imperial College . Personal Communication. July 2012

Imperial College 2012. Annual report and accounts. Accessed online August 2013. https://workspace.imperial.ac.uk/finance/Public/annual_report/annual_report_11_12.pdf

Imperial College 2013 – Energy Policy Centre and Energy Future Labs Website. Accessed online 24/04/2013. http://www3.imperial.ac.uk/icept/ourresearchactivities

Imperial College 2013. Imperial College website about us. Accessed online March 2013. www.imperial.ac.uk

Impetus Waste 2013. Website accessed March 2013. http://www.impetusgroup.co.uk/waste.php

LHP 2010. London Hydrogen Action Plan 2010-2012. London Hydrogen Partnership. Accessed online August 2013 http://www.london.gov.uk/lhp/about/index.jsp

LHP 2012. London Hydrogen Partnership. Personal Communication. July 2012.

LHP 2012a. London Hydrogen Partnership. About website accessed online August 2013 http://www.london.gov.uk/lhp/about/index.jsp

London Assembly 2011. Delivering London's Energy Future. The Mayor's Climate Change Mitigation and Energy Strategy. 2011. http://www.london.gov.uk/priorities/environment/publications/delivering-londons-energy-future-the-mayors-climate-change-mitigation-and-energy-strategy.

London Assembly 2011a. London's Wasted Resource. The Mayor's Municipal Waste Management Strategy 2011. http://www.london.gov.uk/sites/default/files/Municipal%20Waste_FINAL.pdf

London Assembly 2013. Standing Up for London. Holding the Mayor to Account and Working on Behalf of Londoners. Accessed Online August 2013. http://www.london.gov.uk/sites/default/files/London%20Assembly%20-%20Standing%20up%20for%20London.pdf

Natural Resource Wales 2013. Website Accessed 23/10/2013 http://naturalresourceswales.gov.uk/our-work/?lang=en

Northern Echo 2013. Teeside power station halts output, but confirms no job losses. Stephen Hugill. 17th April 2013. Accessed online 24/04/2013 http://www.thenorthernecho.co.uk/business/news/10361884.Teesside_power_station_stops_production/

Simpson D. 2009. The Tees Valley ://www.englandsnortheast.co.uk/Middlesbrough.html accessed March 2013.

SITA UK 2011. Sustainability Report. SITA UK/ SUEZ Environmental.

SITA UK 2012. Driving Green Growth. The role of the waste management industry and the circular economy. SITA UK/ SUEZ Environmental.

SITA UK 2012a. SITA UK. Personal Communication. (Interview) August 2013.

SITA UK 2013. Website accessed March 2013. http://www.sita.co.uk/about-us/our-history

SMART 2012. Information Leaflet. Technology Strategy Board. May 2012

Statistical Bulletin 2010. SB103/2010 Annex E Data Profile Swansea Bay 2010

Statistical Bulletin 2010a. SB103/2010 Annex F Data Profile South East Wales 2010

Tees Valley 2002. Tees Valley Vision Accessed online 24/04/2013 http://icteesside.icnetwork.co.uk/0400business/teesvalley/winter2002/index.cfm?page=1

Tees Valley 2013. Tees Valley Economic Assessment. Tees Valley Unlimited.

Tees Valley Unlimited 2011. Economic and Regeneration. Statement of Ambition.

Temel T., Janssen W., Karimov F. (2002) The Agricultural Innovation System of Azerbaijan: An assessment of institutional linkages. ISNAR Country Report 64.

TfL 2013. Hydrogen Bus Trial, CUTE Project. Transport for London Website. Accessed online August 2013. http://www.tfl.gov.uk/corporate/6585.aspx#section-2

TSB 2013. Technology Strategy Board website accessed March 2013 http://www.innovateuk.org/deliveringinnovation/smart.ashx.

UK Parliament 1998. The Government of Wales Act 19982006 – UK Government Legislation.
UK Parliament 1999. Greater London Authority Act 1999. Accessed online August 2013 http://www.legislation.gov.uk/ukpga/1999/29/contents
UK Parliament 2006. Government of Wales Act 2006, Chapter 32: http://www.legislation.gov.uk/ukpga/2006/32/pdfs/ukpga_20060032_en.pdf
University of South Wales 2013. Website Accessed March 2013. Details of visions of Wales' hydrogen future from the CymruH_2Wales project http://www.h2wales.org.uk/pages/h2-development-in-wales/wales-hydrogen-energy-vision.html
WAF 2012 – Research Interview Jenifer Baxter
WAF 2012a -– Wales automotive Forum . accessed online March 2013. http://www.welshautomotiveforum.co.uk/aboutwaf.aspx
Welsh Government 2009. One Wales: One Planet. Sustainable Development Scheme of the Welsh Assembly Government. Accessed online March 2013 http://wales.gov.uk/topics/environmentcountryside/;jsessionid=7BC04544F08043AD3E5C4EBF5152D645?lang=en 2009
Welsh Government 2010. Climate Change Strategy for Wales. Welsh Government Publication 2010. Accessed online March 2013.http://wales.gov.uk/topics/environmentcountryside/;jsessionid=7BC04544F08043AD3E5C4EBF5152D645?lang=en
Welsh Government 2010a. Towards Zero Waste: The overarching waste strategy for Wales. Accessed online March 2013 http://wales.gov.uk/topics/environmentcountryside/;jsessionid=7BC04544F08043AD3E5C4EBF5152D645?lang=en
Welsh Government 2012. Energy Wales: a low carbon transition. Welsh Government Publication 2012. Accessed online March 2013 http://wales.gov.uk/topics/environmentcountryside/;jsessionid=7BC04544F08043AD3E5C4EBF5152D645?lang=en
Welsh Government 2012a. Climate Change Strategy for Wales. First annual progress report. March 2012 accessed online August 2013. http://wales.gov.uk/docs/desh/publications/120329climateannualreporten.pdf
Williams T. Presentation on Driving towards a greener Wales (date unknown) Wales Automotive Forum. www.bic-innovation.com/knowledge/download/170/

7. IM-TIS Model and Q Methodology: Illustrative worked example "real situation" (London)

Chapters 4 and 6 presented the results of the Q methodology and the application of the IM-TIS model to the regional case study areas of London, Tees Valley and South Wales. The influence of policies on the participants involved in these methods is evident in the results. The Hydrogen from Waste Advocates and Cautionary Environmentalists in the Q methodology are both sensitive to changes in the policy landscape. The results of the case studies show that policy developments in different regions can create public sector led technological innovation systems. These systems are also sensitive to changes in the policy landscape.

In Chapter 2, the literature review identified the breadth and depth of the policies and strategies that are currently in place and provide guidance and regulation in the field of hydrogen from waste. The review showed, however, that there is less clarity about how to assess policy development and review in order to support technological advancement. In some respects this lack of review techniques could be considered as knowledge diffusion. Diffusion of knowledge may occur where a policy maker has all the data at hand to make informed decisions regarding policy development. These policy decisions may be to share knowledge in a particular field with businesses and academia, creating opportunities to build on the knowledge or commercialise existing technologies in line with government policies.

It is in this field of decision making where the IM-TIS model presents an assistive decision making application that is additional to its application to the case studies presented in Chapter 6. It is this aspect of its application that will be demonstrated in this chapter through the use of an illustrative example. From the case study results and literature review, London is the only region to have produced policies that explicitly aim to advance the field of hydrogen from waste. For this reason the London policies will be reviewed in the context of the H_2fW IM-TIS(LN) model. This illustrative example will provide insight into how the policies and the technological innovation system may need to be developed in order to be mutually beneficial. The process of working through this example for the London region contributes to further to addressing all three research questions set out at the beginning of the dissertation:

1. Overall research question: "*What role might hydrogen produced from waste have in the future?"*
2. First research sub-question: *What does the comparison (Aim 2) between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?*
3. *Second research sub-question: How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?*

In addition to demonstrating the IM-TIS as an assistive tool, the Q methodology is being used in this illustrative worked example to provide insight into the role of different actors in the innovation system. The actors may influence the success of an existing policy or the development of a new one.

7.1 Methodology

The methodology for this worked example is described in the literature review for the rock engineering systems model in Section 5.2 of this thesis. In this section a brief summary of this methodology is given.

The process of identifying pathways to create mechanisms aims to support the activation of the interactions within the IM-TIS model. It is suggested that by activating interactions that do not currently exist the overall effectiveness of the TIS will increase, as discussed in Chapter 6. The process is as follows:

- Identify relationships/interactions within the IM-TIS model (using results of London case study).

- Identify relationships/interactions between the functions of innovation that need activating and identify pathways to create interactions between functions (there may be more than one pathway).
- Analyse ESQ coding to show which pathway may have the highest intensity (this is the total ESQ value of the interactions in the pathway).
- Identify how these interactions may be galvanised through the development and/or use of policies.

Harrison & Hudson (2006) describe how the basic use of interaction matrices can offer a systematic approach to identifying and assessing interactions occurring within a system. They only analyse what is happening within an existing system, and what could potentially happen by the existence or removal of certain interactions within the system. This use of the mechanism pathways is used in a preventative way to ensure that failures in engineering projects do not occur. This approach can only be used in advance of an engineering project being finished and cannot be reviewed in the same way the IM-TIS model allows with policy developments. Harrison & Hudson (2006) do not use the mechanism pathways as a way to plan for the future in terms of policy development or to identify the interactions with the greatest potential to improve technological developments. The application to policy described in this chapter also allows for time to be considered, as policies must be developed and action taken over a period of time. In Section 5.1, the IM-TIS model was presented in its original form, developed specifically for this research. In the example in this chapter the model is also presented with the ESQ coding of all of the interactions. These two forms are shown in Figures 7.1 and 7.2 respectively.

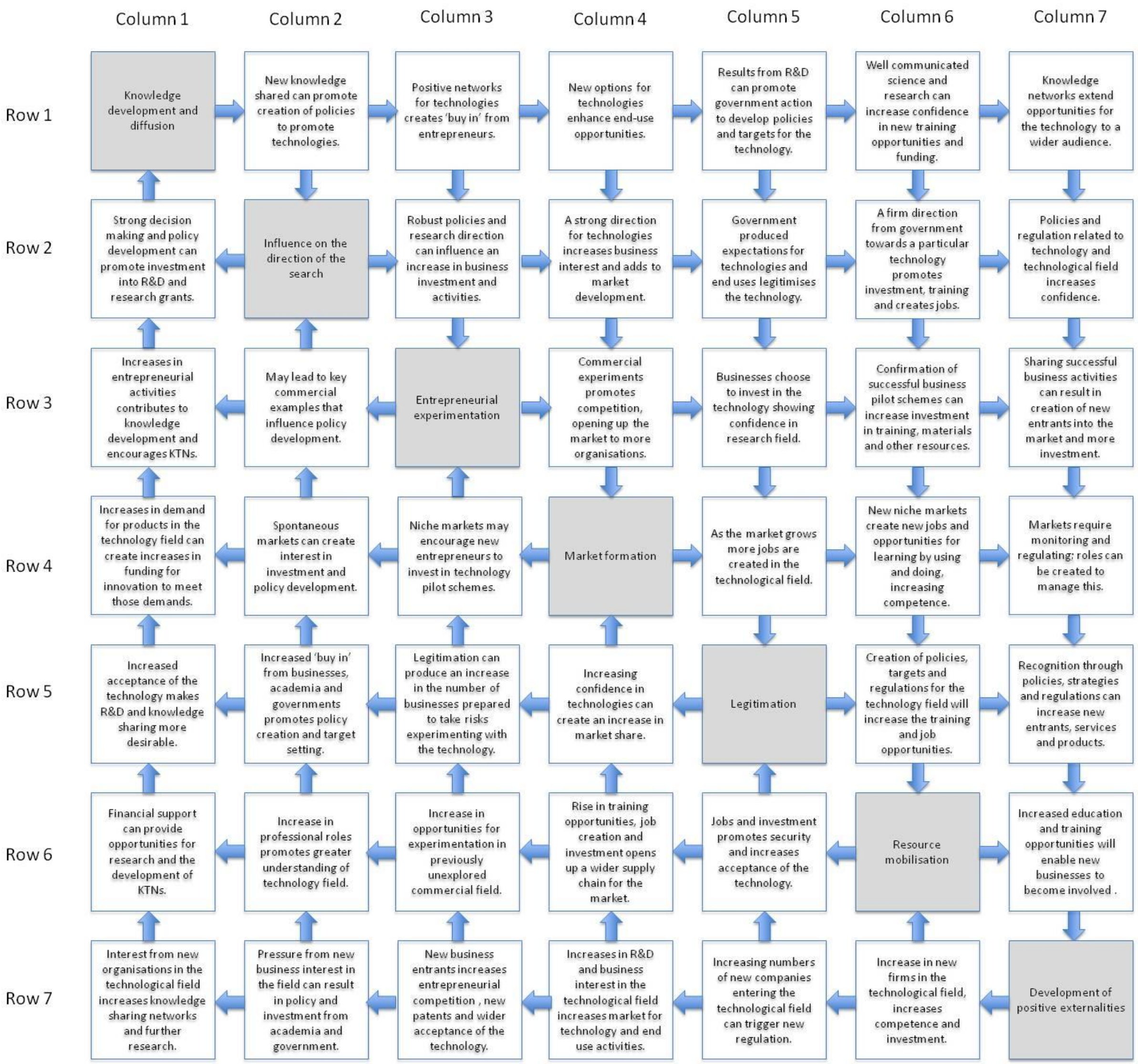


Figure 7.1. The original IM-TIS model with all the relationships between the functions of innovation. (Full matrix available in Appendix 1 CD)

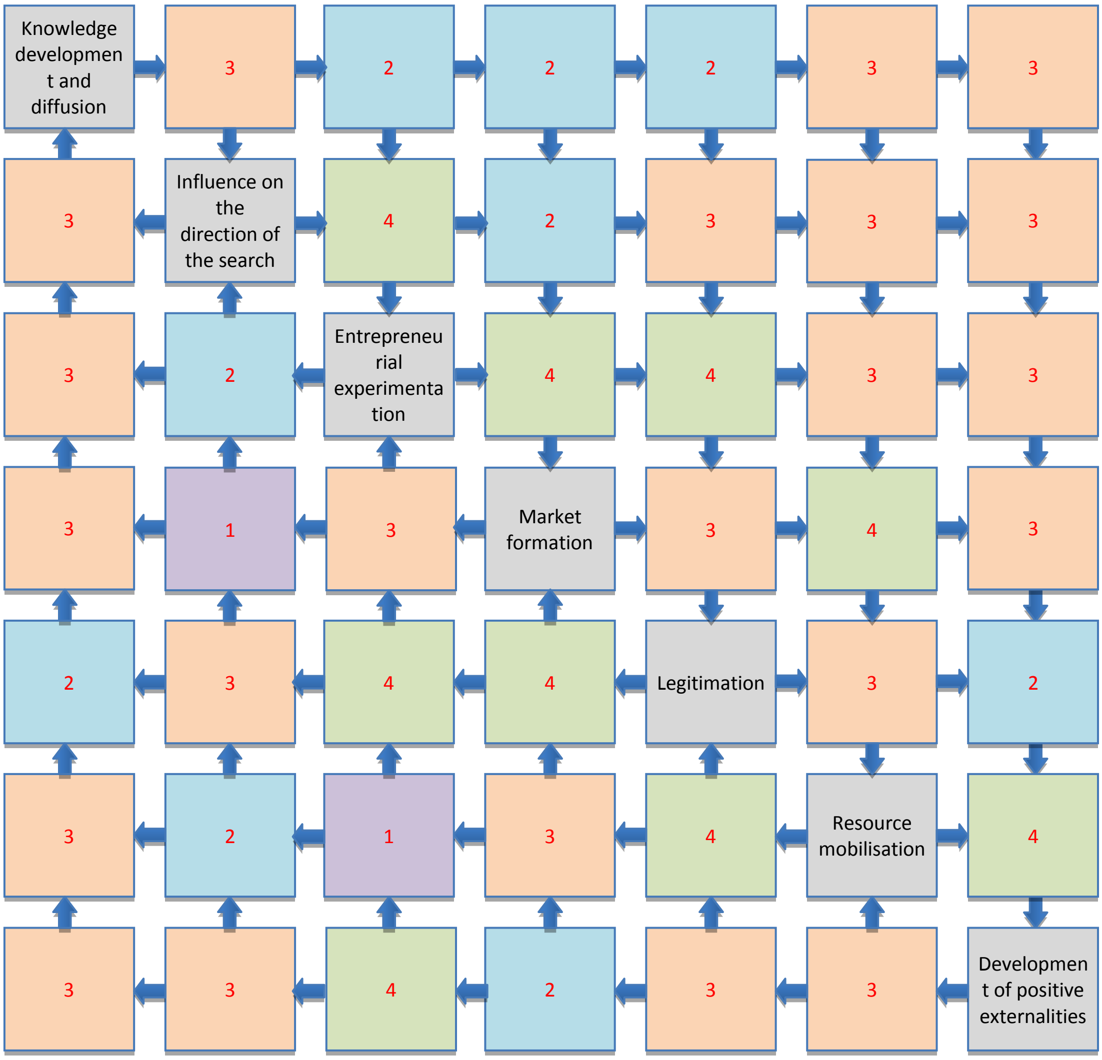


Figure 7.2. The ESQ coding of the interactions in the original IM-TIS model.

In Table 7.1 the ESQ coding for the IM-TIS model is provided. Figure 7.2 shows that the most frequently occurring interactions in IM-TIS are at Level 3; such interactions are considered to be general interactions that occur regularly within a TIS. These may be easily achievable actions that are often done first and lead to initiating the more challenging interactions. The Level 4 interactions would be considered more challenging, but when they do occur create an environment where the technologies aiming for commercialisation and general use can be created and commercialised. For example, *jobs and investments promotes security and increase acceptance of the technology*, seen in the Resource Mobilisation row of Figure 7.1., mobilises resources to enable technological development, as well as contributing to the Development of positive externalities function, a function that occurs as a TIS matures. It is challenging for any government, business or research institution to make this interaction occur without the combined effort of all organisations and actors involved in the TIS. This may mean that other lower Level interactions need to happen first in advance of the activation of this interaction. This is where identifying the pathway mechanisms and their intensities can be useful.

Table 7.1. ESQ coding for interaction levels.

Colour	Scale	Interaction
	0	No interaction
	1	Non critical interaction
	2	An interaction that should occur regularly
	3	Interactions that are general to all TIS
	4	Of particular importance in successful TIS

The coding of the interactions is a key element of this method to develop pathways for achieving relationships between functions and delivering policies.

The distribution of these coded interactions is given in Figure 7.3. The distribution of the interactions confirms that in the original IM-TIS model the majority of interactions are Level 3, meaning that they are common interactions needed for the success of the TIS. It should be the aim of any policy maker or individual aiming to deliver positive outcomes to achieve as many Level 4 interactions as possible. Understanding the significance of these coded interactions enables decisions to be made quantitatively about the intensity of the pathway identified in the IM-TIS model in order to achieve the policy outcomes. This then leads to establishing which pathways within the technological innovation system appear likely to have the greatest impact. Using the IM-TIS model in this manner may provide real-time guidance to decision-makers. In this way, IM-TIS could be considered as a decision-making tool providing further support for the development of particular relationships in a technological innovation system. Furthermore, it is possible for policy makers to use the same process to identify where new policies may need to be made to successfully achieve the transition to a low carbon future using hydrogen production from waste. New policies may be identified where it is clear that without a particular intervention from government, delivery of associated policies within the innovation system may not be achievable.

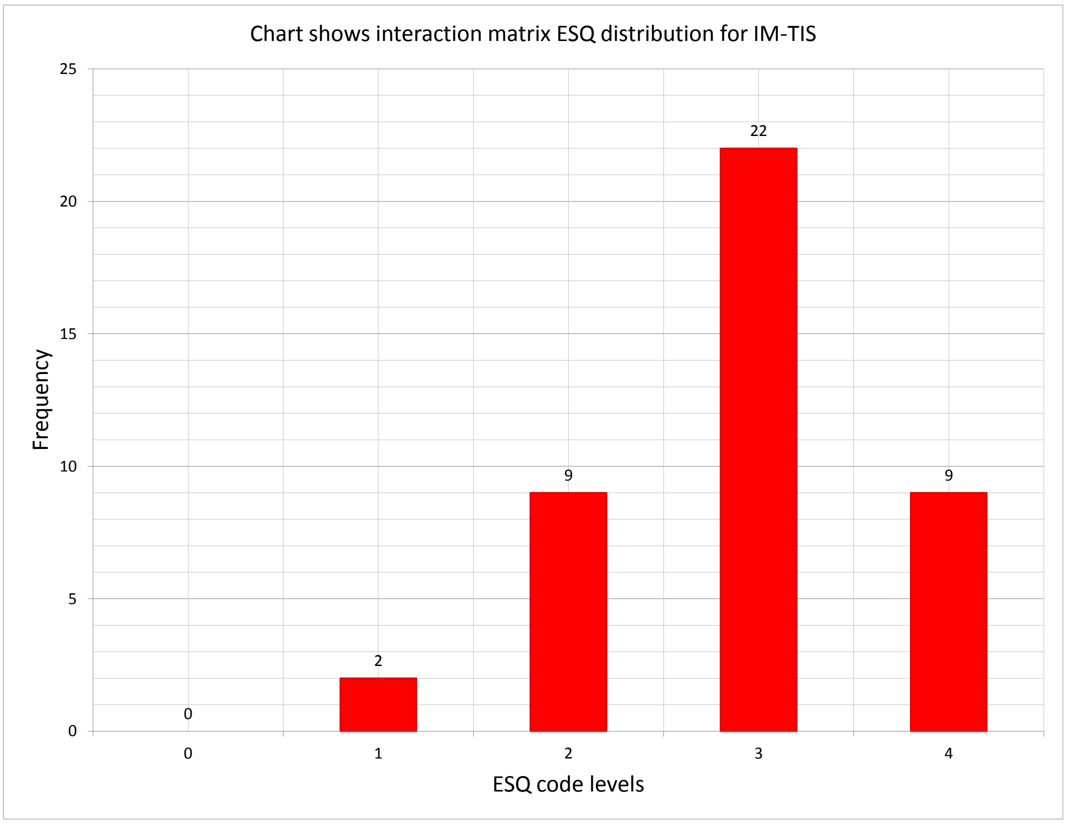


Figure 7.3. Distribution of ESQ coded interactions in the original IM-TIS model.

The minimum length of a pathway in the IM-TIS is one step in the matrix—for example, *knowledge development and diffusion* (seen in Row 1 of Figure 7.1) causes new knowledge to be created. This can lead to *New knowledge shared can promote the creation of new policies to promote technologies*. The intensity of this pathway is represented by the ESQ code for that interaction, which in this case is 3. For the IM-TIS model the number of single step interaction pathways is (7 x 7) – 7 = 42. The number of pathways featuring more than one interaction increases with the number of steps that are taken within the pathway. For example, to achieve a policy initiative it is necessary to manoeuvre along a pathway consisting of:

- *Knowledge development and diffusion to create robust policies* (Row 1 – Figure 7.1)
- *Create a research direction that can increase business investment and activities* (Row 2 Figure 7.1) in the field of hydrogen from waste.

This pathway has an intensity of 9. This is due to the need to pass through the interaction *create positive networks for technologies that increase buy in,* before reaching the destination where *robust policies create research direction increasing business investment*. Taking the ESQ coding values for these interactions in Figure 7.2, it can be shown that this pathway is 3+2+4=9 (seen in Rows 1 and 2 Figure 7.2). The requirement for this pathway could be for communicating the new policies produced from the creation of new knowledge. The network disseminates the new knowledge and policies to the interested businesses that in turn 'buy in' to the technology. In the case study applications of IM-TIS, many of the interactions within the model were absent. The increase in intensity level when all interactions are achieved in the IM-TIS model suggests that the pathway will successfully deliver of the postulated policy.

The following section will work through this methodology, to illustrate how this can be used to review London's policies for hydrogen from waste and plan for the future. This will demonstrate the use of the IM-TIS and Q methodologies in a 'real' situation. These methodologies may be considered as complementary, since the IM-TIS provides pathways and relationships for innovation and the Q methodology shows how actors in those relationships may behave.

7.2 London H_2fW IM-TIS(LN)

The policies that London has developed to advance hydrogen production from waste come primarily from the Greater London Authority's municipal waste strategy (London Assembly 2011). The policies and targets that will be examined using this illustrative example are taken directly from London Assembly (2011 pg: 1):

- Policy 2- Reducing the climate change impact of London's municipal waste management; and
- Policy 3 – Capturing the economic benefits of municipal waste management

The Mayor's municipal waste strategy (London Assembly 2011) states that for Policy 2:

> *"energy generated from municipal waste will need to be no more polluting in carbon terms than the energy source it replaces. Generating low carbon energy from London's municipal waste will play an important part in achieving the Mayor's EPS (emission performance standard), and in achieving the Mayor's decentralised energy and CO_2 reduction targets for London. Waste lends itself well to decentralised energy systems, due to the flexibility of the fuel that can be produced from it. Waste-derived gases from technologies such as anaerobic digestion and gasification, once cleaned, can be piped to local energy centres or to the national gas grid, or can be used directly in gas engines or reformed and used in hydrogen fuel cells, producing electricity and heat where it is required"* (London Assembly 2011 pg: 118).

This last sentence could also support Policy 3. In terms of policy 3, London Assembly (2011) makes the statement:

> *"Energy generated from London's municipal waste, after maximising recycling, could contribute £92 million of savings to London's £4 billion electricity bill and take £24 million off London's £2.5 billion gas bill."*

These policy requirements relate to a number of functions in the innovation system. Table 7.2 shows how components of the above statements supporting Policies 2 and 3 fit in with the functions of innovation components (Bergek et al. 2008) of the IM-TIS model.

Table 7.2. The policy requirements in London for hydrogen production from waste (London Assembly 2011) against the functions of innovation in the IM-TIS model.

Functions of Innovation (Bergek *et al*. 2008)	Policy and strategy components of (London Assembly 2011) relating to Policies 2 and 3 of Mayor's municipal waste strategy
Knowledge development and diffusion	The following is an area where the London assembly may wish to obtain knowledge or learn from others: "Waste-derived gases from technologies such as anaerobic digestion and gasification, once cleaned, can be piped to local energy centres or to the national gas grid, or can be used directly in gas engines or reformed and used in hydrogen fuel cells, producing electricity and heat where it is required."
Influence on the direction of the search	Policy 2 – "Reducing the climate change impact of London's municipal waste management" and Policy 3 – "Capturing the economic benefits of municipal waste management."
Entrepreneurial experimentation	The following is an area where the London assembly may want to see investment or entrepreneurial activity locally: "Energy generated from municipal waste will need to be no more polluting in carbon terms than the energy source it replaces"
Market formation	"Decentralised energy systems will require the creation of local markets to support them. This will also require technology developments to increase the end-use technologies also increasing the markets."
Legitimation	"Generating low carbon energy from London's municipal waste will play an important part in achieving the Mayor's EPS (emission performance standard), and in achieving the Mayor's decentralised energy and CO_2 reduction targets for London."
Resource mobilisation	*Not found in strategy documents (discussed further later in this section)*
Development of positive externalities	"Waste lends itself well to decentralised energy systems, due to the flexibility of the fuel that can be produced from it."

It is now possible to look at the H2fW IM-TIS(LN) model to identify how these different functions are currently met.

To understand how this model can inform the review and development of the policies presented from the Mayor's municipal waste strategy, it is important to decide what these mean and what activities would be expected in order for the policies to be successful. Once these are decided, the matrix can be used to identify and illustrate the gaps, and how pathways can be developed to reach the policy goals. Building on Table 7.2, Table 7.3 presents possible attributes that may be associated with achieving the functions for London

Comparing Table 7.2 and 7.3 it is possible to see which relationships in the IM-TIS model are required in order to deliver elements of the policies for London presented in Table 7.2. Strategy documents that are designed to deliver particular policies for the government may present as ideas rather than a strict set of activities that need to be carried out. Where action plans that do have target activities are given, there is a burden on the government to deliver the policy as defined at the beginning of the process. This may reduce the opportunity to review and adapt policies to suit a changing technological and social environment, as described by Nill & Kemp and presented in section 2.4 of the literature review (Nill & Kemp 2009).

The results of the IM-TIS model for London show which of the relationships within each function exist at the time of the case study interviews, as presented in Chapter 5. From this data, it is possible to do further analysis to identify which of the relationships could deliver greatest impact in order to deliver the policy. Table 7.3 brings together the relationships in IM-TIS and the statements on the Policies 2 and 3 from Table 6.2. With the identification of functions appropriate to deliver the policies, the next step is to identify the pathways with the greatest intensity. These are the pathways which may be considered the most likely to deliver London's policies for hydrogen from waste.

Table 7.3. The relationships from the IM-TIS model that could support the policies in the Mayor's Municipal Waste Strategy (London Assembly 2011).

IM-TIS model relationships	Policy components relating to Policies 2 and 3 of Mayor's municipal waste strategy (London Assembly 2011)
Knowledge development and diffusion - New knowledge shared can promote creation of policies to promote technologies - Positive networks for technologies create 'buy in' from entrepreneurs. - New options for technologies enhance end-use opportunities. - Results from R&D can promote government action to develop policies and targets for the technology. - Knowledge networks extend opportunities for the technology to a wider audience - Well-communicated science and research can increase confidence in new training opportunities and funding.	The waste strategy discusses potential new applications, including the waste-derived gases from technologies such as anaerobic digestion and gasification, once cleaned, can be piped to local energy centres or to the national gas grid, or can be used directly in gas engines or reformed and used in hydrogen fuel cells, producing electricity and heat where it is required.
Influence on the direction of the search - Strong decision making and policy development can promote investment into R&D and research grants - Robust policies and research direction can influence an increase in business investment and activities. - A strong direction for technologies increases business interest and adds to market development - Government produced expectations for technologies and end uses legitimises the technology - A firm direction from government towards a particular technology promotes investment, training and creates jobs - Policies and regulation related to technology and technological field increases confidence.	Policy 2 - Reducing the climate change impact of London's municipal waste management and Policy 3 – Capturing the economic benefits of municipal waste management. Both policies give direction to the search.
Entrepreneurial experimentation - Increase in entrepreneurial activities contributes to knowledge development and encourages Knowledge Transfer Networks (KTNs). - May lead to key commercial examples that influence policy development. - Commercial experiments promote competition, opening up the market to more organisations. - Businesses choose to invest in the technology showing confidence in research field. - Confirmation of successful business pilot schemes can increase investment in training, materials and other resources.	Energy generated from municipal waste will need to be no more polluting in carbon terms than the energy source it replaces. This will require experimentation by entrepreneurs.

- Sharing successful business activities can result in creation of new entrants into the market and more investment.	
Market formation - Increases in demand for products in the technology field can create increases in funding for innovation to meet those demands. - Spontaneous markets can create interest in investment and policy development. - Niche markets may encourage new entrepreneurs to invest in technology pilot schemes. - As the market grows more jobs are created in the technological field. - New niche markets create new jobs and opportunities for learning by using and doing, increasing competence. - Markets require monitoring and regulating; roles can be created to manage this.	The waste strategy envisages the development of decentralised energy systems.
Legitimation - Increased acceptance of the technology makes R&D and knowledge sharing more desirable. - Increased 'buy in' from businesses, academia and governments promotes policy creation and target setting. - Legitimation can produce an increase in the number of businesses prepared to take risks experimenting with the technology. - Increasing confidence in technologies can create an increase in market share. - Creation of policies, targets and regulations for the technology field will increase the training and job opportunities. - Recognition through policies, strategies and regulations can increase new entrants, services and products.	The strategy states that generating low carbon energy from London's municipal waste will play an important part in achieving the Mayor's EPS (emission performance standard), and in achieving the Mayor's decentralised energy and CO_2 reduction targets for London.
Resource mobilisation	*Discussed further below*
Development of positive externalities - Interest from new organisations in the technological field increases knowledge sharing networks and further research. - Pressure from new business interest in the field can result in policy and investment from academia and government. - New business entrants increase entrepreneurial competition, new patents and wider acceptance of the technology. - Increases in R&D and business interest in the technological field increases market for technology and end use activities. - Increasing numbers of new companies entering the technological field can trigger new regulation.	The strategy describes the advantages of using waste in decentralised systems, stating that waste lends itself well to decentralised energy systems, due to the flexibility of the fuel that can be produced from it.

From Tables 7.2 and 7.3 it is suggested that the policy statements made in the Mayor's municipal waste strategy do not reflect the resource mobilisation function. This means that in order to achieve delivery of these policies the resource mobilisation relationships in the IM-TIS will need to be met, but how London's policies aim to do this is not evident. Suggestions of various options for achieving resource mobilisation will be made through pathway identification using the IM-TIS model.

This worked example looks specifically at the way the strategy addresses hydrogen generated from waste and not more broadly at the way the strategy addresses improving skills or creating a green work force. It is possible that some components of the resource mobilisation function could be addressed in those parts of the strategy.

For this illustrative example, two particular functions and their relationship to the policies will be addressed; they are shown in Figure 7.4 below. These are the functions of:

- Influence on the direction of the search (Row 2) and
- Market formation (Row 4).

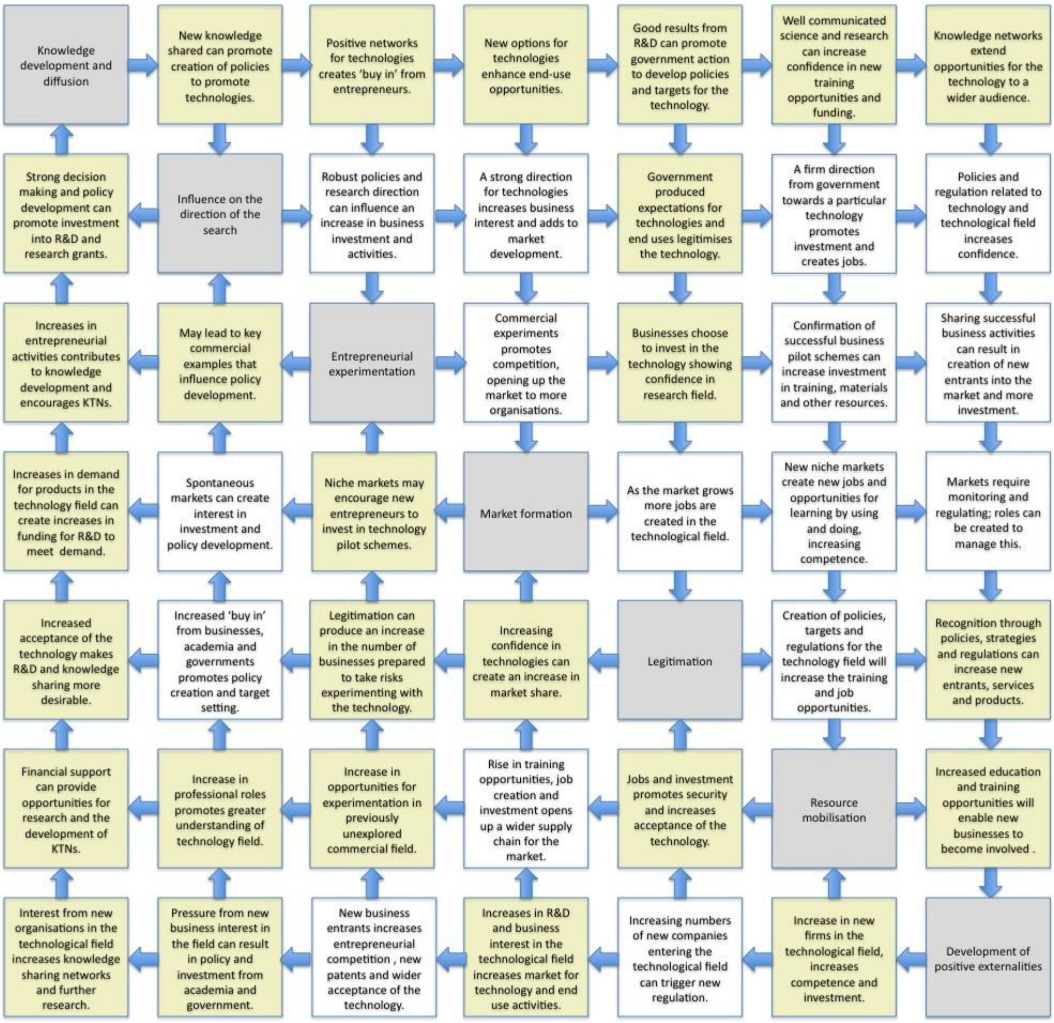


Figure 7.4 The active relationships (highlighted in yellow) in the H2fW IM-TIS(LN) case study.

7.2.1 Function – Influence on the direction of the search

The policies in the Mayor's municipal waste strategy provide high-level direction to the research, development and entrepreneurial activities that could be undertaken. UK Government may support activities in these sectors, if they are considered to be working towards achieving the Greater London Authority's policy direction. The policies being worked through in this example are:

- Policy 2 - Reducing the climate change impact of London's municipal waste management; and
- Policy 3 – Capturing the economic benefits of municipal waste management.

Example 1

From the H_2fW IM-TIS (LN) case study, the results shown in row 2 suggest that under the influence on the direction of the search function, two of the relationship interactions exist. They are:

- Strong decision making and policy development can promote investment into R&D and research grants and
- Government produced expectations for technologies and end uses legitimise the technology.

This means that to create the greatest impact for this function according to IM-TIS, four further relationship interactions need to occur. These are:

- Robust policies and research direction can influence an increase in business investment and activities
- A strong direction for technologies increases business interest and adds to market development
- A firm direction from government towards a particular technology promotes investment, training and creates jobs
- Policies and regulation related to technology and technological field increases confidence.

For this function, the successful pathways to achieving these relationship interactions could be shortened. This is due to the complete existence of all the relationship interactions in the knowledge development and diffusion function seen in Row 1. Additionally, all of the functions impacting on knowledge development and diffusion also exist, as seen in Column 1.

The majority of interactions that could cause the creation of the interactions associated with the influence on the direction of the search function are seen in Row 1. Knowledge development and diffusion and the entrepreneurial experimentation function seen in Row 3 may also influence these interactions.

Starting with the shortest pathway from *Knowledge development and diffusion* to activate a currently absent relationship interaction *robust policies and research direction can influence an increase in business investment and activities*, the pathway takes the route through:

- The knowledge development and diffusion function, and moves through
- Knowledge shared can promote the creation of policies to create technologies, into
- Positive networks for technologies create buy in from entrepreneurs.

The pathways being described can be seen in red in Figure 7.5, which shows a section of the matrix. Figure 7.5 shows three example routes to different missing interactions. Example 1 is the short route starting at Knowledge development and diffusion. Example 2 is the longer route starting at the same point and Example 3 is indicated by the red route in rows 3 and 4. All three examples are described in this section and section 7.2.2.

It is at this point that a policy maker reviewing the strategic document to deliver policies for London would need to consider what is happening in these relationship interactions. Establishing how to then move into the interaction of *Robust policies and research direction can influence an increase in business investment and activities* is required. The matrix suggests that knowledge is being shared in order to create these policies and that networks exist that are sharing new technological information (seen in row 1). Faced with this evidence, it would appear reasonable for a policy maker to ask the question: "Why are businesses not buying into this technology?"

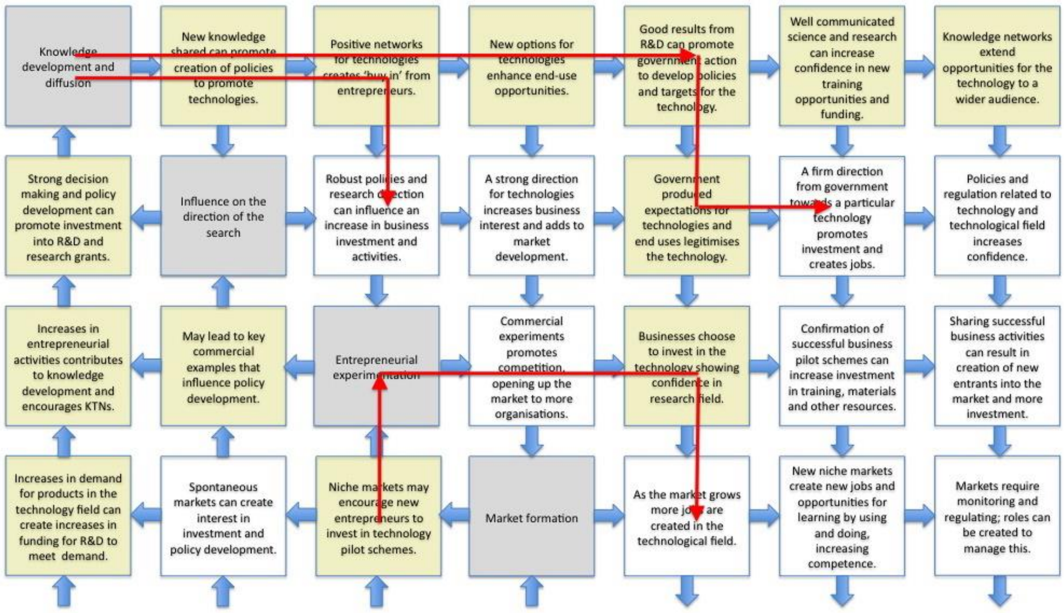


Figure 7.5. Selected routes for policy development pathways through sections of original IM-TIS matrix.

The results of the Q methodology could then be used to help understand the role and behaviour of stakeholders or actors involved in the interactions that need to be created. It may be possible for policy makers to influence the creation of interaction relationships. A summary of the Q methodology factor identities revealed by the Q methodology presented in Chapter 4 is shown in Table 7.4.

Note: The Q methodology factor identities can be used to pose questions and establish how actors may behave in the innovation system that is contributing to policies. However, it is important to remember that the identities revealed by the Q methodology in Chapter 4 were not established for the case study regions.

Table 7.4. Summary of each of the Q methodology identities presented in Chapter 4.

Q Methodology Factor Identity	Summary of Identity
Hydrogen from waste advocates	Respondents classified in this identity actively advocate and think positively about hydrogen from waste and other energy from waste technologies. The demographic of this factor is predominantly chemists working on new technologies to produce hydrogen, and hydrogen technology experts. They are advocates of new and emerging technologies, such as dark fermentation, and they promote the use of combining new technologies with old, for example, using the existing gas grid for transporting hydrogen as a fuel.
Cautionary Environmentalists	Respondents classified as cautionary environmentalists advocate changes that bring environmental and societal benefits. They believe strongly that all technologies pose a risk and that hydrogen-producing technologies are no different. Although they accept that hydrogen will have a role in a future energy system, they are not clear as to the size of this role. They do not believe that hydrogen should be produced unless there is a market for it and that companies (especially in the automotive industry) must buy into the idea of hydrogen as a future energy source before it is taken further.
Hydrogen Technologists	This group believes strongly that hydrogen will have a large role to play in the future as a fuel and energy provider. The hydrogen technologists believe that the UK must keep up with other leading countries in the transition to a hydrogen economy and that there are good emerging technologies that can assist with the transition in the UK. This group shows that they are aware of the risk involved in all technologies and that in the UK some assistance with developing hydrogen plants and establishing an innovation system for the creation of hydrogen from waste are both important elements in moving forward.

Possibilities that are impacting on the production of robust policies that encourage business buy-in to the sector may now be considered. For example, are stakeholders who fall under the Cautionary Environmentalists group likely to be responsible for the development of the robust policies that may increase business buy-in? The factor identity for this group implies that it does not believe that hydrogen should be produced without an existing end-use market. This is particularly the case where the automotive industry is likely to be the end user. In London the production of hydrogen is to support the activities of the London Hydrogen Partnership in delivering their action plan (LHP 2010). The aims of LHP Action Plan are:

1. “A key role of the Greater London Authority GLA family is to support the shift to lower environmental impact road vehicles through providing support, infrastructure, incentives and leading by example.”

2. “The GLA are promoting new, cleaner technologies, encouraging people to use cleaner modes of transport wherever possible and when they do drive, to adopt eco-driving measures.”

This could mean that the ability of the innovation system to deliver this part of the Municipal waste strategy policies is reliant on whatever level of market for hydrogen is created through the activities of the London Hydrogen Partnership. Evidence of the market or prospects for the market may be required to influence policy makers promoting and incentivising automotive buy-in. This was a possible stipulation of the Cautionary Environmentalists, as exposed by the Q methodology. The robust policies that are proposed by IM-TIS may attempt to address the concerns of those in the Hydrogen Technologist group presented in Table 7.4. This group have already bought-in to the concept of hydrogen technologies. Without the leadership from policy makers, who may be represented by the Cautionary Environmentalist group, it may not be possible for Hydrogen Technologists to attract investment for their technologies.

A further consideration for a potential policy-maker is that of the possible conflict between the IM-TIS relationship that looks for ‘robust’ policies and the role of ‘adaptive’ policy making that responds to changing circumstances. It might be possible for the policy maker to consider that identifying a technology such as hydrogen fuel cells in vehicles is both robust and allows for the technology to adapt with time. This is because ‘hydrogen fuel cells’ is a generic term for a number of different possible technologies to be developed that are hydrogen fuel cells; different technologies, such as catalysts and membranes within the fuel cells use hydrogen differently to produce energy. The robustness comes from the statement that the policy is looking for the energy to be produced through fuel cells rather than through a hydrogen combustion engine or batteries, for example.

In summary, to begin to create the interaction of "Robust policies and research direction can influence an increase in business investment and activities", the IM-TIS approach helps to identify that the following may be useful:

- Establish the actors involved, i.e. automotive policy makers and the automotive industry.
- Obtain the appropriate evidence that may influence the automotive policy makers.
- Encourage leadership through the networks in associated interactions of the IM-TIS matrix, to influence policy makers.
- Create clusters or networks of automotive industry actors to share details of developing policies and subsequently business "buy-in".

Finally, as noted, in creating this pathway the intensity can be calculated. It is a three-step pathway featuring one Level 2 and one Level 3 interaction, with the desired interaction being a critical level 4 interaction. The total intensity of this pathway is 9. This pathway intensity is not high, due to the existing interactions including a level 2 interaction. The higher the intensity of the pathway, the more the components within the pathway are contributing to the success of the TIS. The greater the intensity of pathways, the more interactions in the IM-TIS model exist and so increase the overall efficiency of the system. The creation of this interaction in the H_2fW IM-TIS(LN) would contribute to reducing CO_2 emissions and capturing the economic value of London's municipal wastes, as directed by the policies described above.

<u>Example 2</u>

Now we consider the creation of a second interaction within the same function: *A firm direction from government towards a particular technology promotes investment, training and creates jobs*.

The process described in Example 1 can be used to consider how this relationship might be created. The pathway for developing this interaction can be seen as the longer red route shown in Row 1 of Figure 7.5. This route has been chosen as all relationships in Row 1 exist. The pathway then moves into Row 2 at the first possible existing interaction, which is *Government produced expectations for technologies and end uses legitimises the technology*. The next step is to attempt to create the conditions that will support the interaction of *A firm direction from government towards a particular technology promotes investment, training and creates jobs*.

In some respects this is a similar interaction to that described in Example 1, with the reference to a firm direction from government. This could be considered to take the form of new policies. The focus here is promoting investment in training and jobs. This could require business, academia and governments to recognise the value in the expansion of this technological field, in this case the sustainable production of hydrogen from waste.

The Q methodology may give some insight into the actors involved in creating the conditions required to activate this relationship within London and subsequently the IM-TIS matrix. Possible conditions may include:

- Active pilot programmes for hydrogen from waste.
- Active hydrogen end-user projects.
- Conferences and workshops that cover hydrogen production.
- Incentives from governments to utilise hydrogen in energy and transport systems.

The Hydrogen from Waste Advocates identified by the Q methodology may fulfil the role of networking and influencing further training and job growth. This group are advocates of the hydrogen from waste technological field and the group is made up from academics and commercial chemists. These groups could be influenced to effectively communicate their innovations and science through conferences aimed at business end-users and governments. The Cautionary Environmentalists are the group that are most likely to be creating the policies that support hydrogen and associated training programmes. They may need to be convinced that providing the firm direction required will provide the results needed to meet London's policies sustainably. Hydrogen Technologists may also have a role here being encouraged to participate in trials and pilot schemes that can assist in legitimising the technologies and grow acceptance of hydrogen as a fuel in London communities.

A policy maker or reviewer aiming to create the desired conditions for this interaction nwould need to decide what actions they could undertake in order to galvanise the actors in the innovation system to act in the right direction. Actions could include:

- Establish and engage the actors involved in the creation of the relationship.
- Encourage academic actors to share their innovation and science in a positive way through conferences and workshops aimed at businesses and government.
- Work with end-users to establish community pilot programmes to increase acceptance of the technology and legitimise its place in the energy system.

Achieving these actions could help London to meet the challenges of providing a highly skilled work force to deliver the policies of the Mayor's Municipal Waste Strategy (London's Wasted Resource 2011). This pathway is made up of six steps and has an intensity of 15, identified from Figure 7.2 and Table 7.1;. it is made up of three Level 2 interactions and three Level 3 interactions. There are, however, no interactions of particular importance to the success of the TIS (Level 4 interactions) in this pathway. This could suggest that finding an alternative pathway that includes Level 4 interactions on its route may be more advantageous to a policy maker or reviewer attempting to deliver on London's ambitions.

7.2.2 Function -Market Development

In this section one example will be considered; this is shown as the market development pathway in Figure 7.5.

Example 3

In this example the relationship being considered is: *As the market grows more jobs are created in the technological field*. To reach this interaction a pathway has been identified shown in the lower part of Figure 7.4. Following this route as shown, an additional interaction needs to be activated. The interaction is the relationship between the functions of Entrepreneurial Experimentation and Market Formations and is described as: *Commercial experiments promote competition, opening up the market to more organisations*. Following the route of this pathway means that *Commercial experiments promote competition, opening up the market to more organisations* should be considered first.

The steps that were used in the first two examples can be followed to attempt to create appropriate conditions for the success of this relationship interaction. This relationship focuses on the establishment of pilot programmes carried out by commercial production and end-use operators. This requires engagement with the Q methodology group identified as Hydrogen Technologists. It is this group that will be primarily responsible for the development of pilot programmes in the commercial hydrogen production and end-users sector. There may also be a place for the Cautionary Environmentalists, some of whom may be interested in running trial waste to hydrogen projects as part of a waste management scheme. Cautionary Environmentalists may also be responsible for government grants that support pilot programme activities. The Hydrogen technologists could be interested in growing the hydrogen sector. It is likely to be in their interest for the government to create the appropriate “robust” policies identified as important milestones described in Examples 1 and 2. To engage this group in the process, those aiming to deliver the policies for London may need to:

- Create funding opportunities or
- Create zones in London that support the establishment of commercial pilot schemes.

The route of this pathway then moves down into the market development row and the creation of the conditions for the final destination of: *As the market grows more jobs are created in the technological field*. Actors that may be involved in this relationship could potentially come from all three Q methodology identities. Possible job opportunities could occur in all identities and across business, academia and government sectors. However, in order to achieve these job opportunities, many elements of the IM-TIS might be required. It could be the case that the whole technological innovation system needs to be successful for the market to grow. This may lead to the creation of new jobs in the technological sector creating positive externalities through a broader supply chain. To achieve this goal a decision-maker aiming to deliver the London policies may need to:

- Engage with academia, business and government.
- Create networks that encourage partnership working and development of pilot programmes.
- Influence local authorities to create zones where the hydrogen market could receive incentives to grow.
- Work across the innovation system to establish opportunities for the development of positive externalities, including job growth and development of the supply chain.

Success in these areas may deliver the requirements identified in Table 7.3 for the creation of decentralised energy systems.

This pathway contains four steps and has an intensity of 14, containing two Level 3 interactions and two Level 4 interactions. Considering that this is a short pathway containing two interactions that are of particular importance to the success of a TIS, this pathway may be a critical pathway. A critical pathway could be a route that activates more than one Level 4 interaction—an interaction of particular importance to the success of a TIS.

7.3 Concluding Comments

This worked example illustrates how the IM-TIS model and the Q methodology results can be used together to support the development and review of action for the delivery of policies, in this case policies relating to London's municipal waste strategy.

The method used in this example is proposed as a useful approach to policy, strategy and action plan development. It is the first time that the two methodologies have been combined together to produce an understanding of the behaviour of actors involved in a TIS. It has shown that by understanding who may be involved in activating relationships between functions of innovation we are able to establish why they may not be occurring. This provides a further opportunity to work with the different groups of actors provided by the Q methodology, to alleviate their concerns and create networks between them. It is not suggested that this is the only use for the Q methodology and IM-TIS. They can be used independently or in combination with other models, as identified in sections 2.4 and 3.2.

Harrison & Hudson (2006) have used the projected pathways technique using an algorithm that identifies the routes with the greatest intensity. They have not pursued or developed routes for further consideration as presented here. In this example a manual approach has been used.

As suggested at the beginning of this chapter, this illustrative example has contributed to addressing the three research questions:

1. Overall research question: *What role might hydrogen produced from waste have in the future?* It has been established that hydrogen from waste is seen as a good renewable energy source (London Assembly 2011) and that the individuals involved (Q methodology) in activating interactions within the TIS can do so with some guidance from policy assessment and review (IM-TIS).
2. First sub research question: *What does the comparison between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?* The IM-TIS model was able to guide the assessor through the interactions to meet a desired goal in order to achieve the policy outcomes. This also provided the assessor with ideas on how interactions between actors and institutions within the TIS could be achieved.

3. *Second sub research question: How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?* The Q methodology provided insight into how the individuals active within the TIS may respond to the different interactions within the system.

In this chapter the two research methods of Q methodology and IM-TIS have been brought together to show how they can be used together to address the delivery or review of policies. This use for the methods supports the idea of adaptive policy making and, as shown in the case of London's waste strategy, could be of value in developing policies for the development of hydrogen from waste.

The applications of the IM-TIS model and the contribution to achieving the research question will be discussed further in Chapter 8 Discussion.

7.4 References

Bergek A., Jacobsson S., Carlsson B., Lindmark S., Rickne A. Analysing the functional dynamics of the technological innovation systems: A scheme of analysis. Research Policy 37 (2008) 407–429

Harrison J.P., Hudson J.A. Comprehensive hazard identification in rock engineering using interaction mechanism pathways. ARMA/USRMS 06-1144 (2006) Proc. 41st US Rock Mech. Symp., Golden, Colorado, US

LHP 2010. London Hydrogen Action Plan 2010-2012. London Hydrogen Partnership. Greater London Authority. Accessed online May 2013. http://www.london.gov.uk/lhp/documents/LondonHydrogenActionPlan2010-12.pdf

London Assembly 2011. London's Wasted Resource: The Mayor's municipal waste strategy. 2011. Accessed online August 2013. http://www.london.gov.uk/sites/default/files/Municipal%20Waste_FINAL.pdf Greater London Authority Publication.

Nill J., Kemp R. Evolutionary approaches for sustainable innovation policies: From niche to paradigm. Research Policy 38 (2009) 668–680

8 DISCUSSION OF FINDINGS

This thesis has introduced three methods, Q methodology, IM-TIS model and IM-TIS pathway mechanisms, and applied them to the hydrogen production from waste field. These methods have been adapted and developed in order to carry out investigations to gain insight into and address the overarching research question: *What role might hydrogen produced from waste have in a future low carbon energy system in the UK? This question was explor*ed with the aid of two research sub-questions:

1. *What does the comparison between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?*
2. *How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?*

These sub-questions were explored using the two primary research tools presented in this thesis, Q methodology and the IM-TIS model. Research into sub-question 2 used the Q methodology to provide characterisation and greater understanding of the groups of actors involved in the technological innovation system for hydrogen from waste across the UK. The novel adaptation of the RES method, which led to the newly developed conceptual IM-TIS model, was applied to 'real' situations across three regions of the UK. This application has helped to understand how the conceptual model compares to 'real' situations, in answer to sub-question 1. During the course of this research, the process of addressing Question 1 relied on on the results in connection with Question 2, consequently in the following discussion Question 2 is considered first.

Chapter 4 presented the results of the Q methodology. This process was used to identify different groups of experts working in the hydrogen production from waste field and subsequently involved in the technological innovation system surrounding it. The Q methodology revealed three identities that improve knowledge of groups of actors and their behaviour within the system. Chapters 5 and 6 present the development and application of the IM-TIS model. IM-TIS has been used to develop greater understanding of the technological innovation system for hydrogen production from waste in three UK regions. The IM-TIS model is a new conceptual framework for considering the relationships between functions of innovation.

Chapter 7 used the IM-TIS model in a further application that identifies pathways as an assistive tool for policy development and review. This was presented as an illustrative worked example that demonstrated how these methods could be used in collaboration between government, academia and business, to proactively deliver and review policies that support hydrogen from waste projects. The pathway application has been applied to the London case study region and the strategies associated with hydrogen production from waste in London.

This chapter discusses and brings together the findings from the application of the three methods. The impact of revealing group identities (via Q methodology) for individuals involved in the TIS is discussed in section 8.1. This is followed in section 8.2 by a discussion on the suitability of the IM-TIS for understanding the relationships between the different functions of innovation when applied to case studies in the UK. In this section the relevance of the dominant and subordinate functions to the success of the TIS, as well as differences between public and private sector led systems is considered. In section 8.3 the application of IM-TIS and combined use with Q methodology is considered. How the use of this new knowledge can assist the future of hydrogen production from waste in a UK setting is discussed. Finally section 8.4 discusses the future role of hydrogen from waste in a low carbon UK energy system.

The literature surrounding technological innovation systems and functions of innovation provides conceptual frameworks. These frameworks offer a base from which further understanding of what comprises each function has been developed. The literature presented in section 2.4 details a number of studies (Negro *et al*. 2007; Negro *et al*. 2008; Suurs *et al*. 2010; Hawkey 2012; Breukers *et al*. 2013;) that have applied the basic functions of innovation framework to particular phenomena. These studies have focused on identifying activities that fit the criteria for the different functions, as presented in section 2.4; drivers, system blockages and challenges for the phenomena have been identified through these studies. The literature review suggested, however, that there are significant opportunities for further detailed analysis of the relationships between the functions, especially relating to the influence and impact that one function may have on another and across the system as a whole (Truffer *et al.* 2012). In addition to this, Truffer *et al*. (2012) also described the need to for TIS studies to consider how TIS may change over time.

8.1 Impact of understanding group identities involved in TIS (Q methodology)

Truffer *et al.* (2012) identified a gap in the current TIS literature that suggested that although the predominant view is that TIS actors are working together towards the overall goal, firms often work towards a strategic goal for their own benefit rather than that of the overall system. This means that further analysis of actor roles and strategies in TIS studies is required.

The relationships and interactions between each of the functions of innovation rely heavily on the individuals who work within each function and across functions. Having additional insight into the likely response from different TIS actors to a particular activity within the TIS allows for system adjustments. This means that if an individual is aiming to develop a particular activity or relationship within a TIS they are more able to accommodate the likely behaviours that the TIS actors will exhibit.

The Q methodology revealed three identities, Hydrogen from Waste Advocates, Cautionary Environmentalists and Hydrogen Technologists, all of whom are TIS actors in the case of hydrogen from waste in the UK. The impact of understanding these three different types of actors and their behaviours within an active TIS can be seen clearly in the worked example in Chapter 7.

In the case of hydrogen production from waste TIS in the UK, the group identities revealed by Q methodology showed that although there was some agreement between TIS actors on the future of hydrogen production from waste, there are still a number of differences that will hold up the process of commercialisation for hydrogen technologies. For example, from the results given in section 4.4, Hydrogen Technologists are far less concerned about the sustainable development implications of hydrogen production from waste than their colleagues in the Cautionary Environmentalist and Hydrogen from Waste Advocate groups. This type of fundamental difference between actors working within a TIS would need to be addressed through a number of activities within the different functions of innovation; these may include *Knowledge development and diffusion, Influence on the direction of the search* and *Creation of positive externalities*. If this kind of issue is not confronted and resolved the outputs of the TIS may always be limited, as not all actors would be working towards shared goals.

The results of the Q methodology have begun to address some of the concerns voiced by Truffer *et al*. (2012), but have also confirmed that TIS actors remain fragmented in the case of hydrogen production from waste in the UK.

8.2 The Development of a new conceptual model for TIS: Interaction Matrix-Technological Innovation System (IM-TIS)

As noted earlier in this chapter, the literature review identified a need to investigate in more detail the relationships between each function of innovation (Truffer *et al.* 2012) within the functions of innovation framework (Bergek *et al.* 2008). To address this gap, the development of the IM-TIS model, an adapted version of the original RES model, combined with the functions of innovation conceptual framework, provided an opportunity to develop knowledge about the relationships between the functions in the system. This was a key element in the analysis of the potential for hydrogen from waste in the UK. It is suggested that this system could be both visually and conceptually accessible to non-experts. This accessibility means that the model could act as a supportive decision-aiding tool for actors working to deliver hydrogen from waste technologies. The model presents a conceptual system and an interaction matrix. The interactions described in the IM-TIS model are the suggested relationships between the functions of innovation. These interactions are generic in nature. Consequently, due to the non-technology specific nature of the relationships in IM-TIS, this new model can be applied to other technological fields beyond the field of hydrogen from waste.

The IM-TIS model was applied to three case study regions (see Chapter 6) and revealed two typologies for emerging technological innovation systems supporting hydrogen from waste. The first is the *public sector led* innovation system. This type of system was found in the South Wales case study region and the London case study region. In both of these regions, the potential for hydrogen from waste was supported directly or indirectly by a number of waste and energy policies. The policy landscape for these two regions is described in the case study sections 6.3–6.9. Key features of that landscape include a higher occurrence of government and academic led interactions within in the matrix. This is combined with specific policies for waste, anaerobic digestion and energy for each region. In addition to these features, in both instances the majority of case study participants were from public sector organisations. The second TIS type is *private sector led* and was found in the Tees Valley case study. This type of TIS is categorised by a higher number of business and enterprise based interactions occurring within the IM-TIS model, along with limited or no policies specific to the region.

In the two public sector led innovation systems (South Wales and London), the evidence presented in sections 6.6 & 6.8 suggests that they follow the path of the original system presented in the development of IM-TIS in section 5.2 It may be the case that the presence of the policies specific to South Wales and London (sections 6.5 & 6.7) supports the development of hydrogen production from waste, providing reassurance about future prospects to the academic and business sectors. However, the growth of research and development activities in both business and academia is not solely reliant on the development of UK government policies. The reassurance and risk reduction presented by the policies may, however, be the trigger needed for a business to make an investment in a particular project promoting hydrogen production from waste. In the academic sector the policy objectives encouraged by government may be the foundation for particular research council or other funding programmes directed at achieving a specific policy outcome. These policies may also influence decisions relating to a particular project. This reinforcement of a technological field by government policies may encourage the activation of new relationships within the matrix over time.

As described above, the second technological innovation system type is the private sector led system. It is suggested that the system studied in the Tees Valley case study region represents a system of this kind. Some of the differences between the two systems are extracted from the case study results chapter and shown in Figure 8.1.

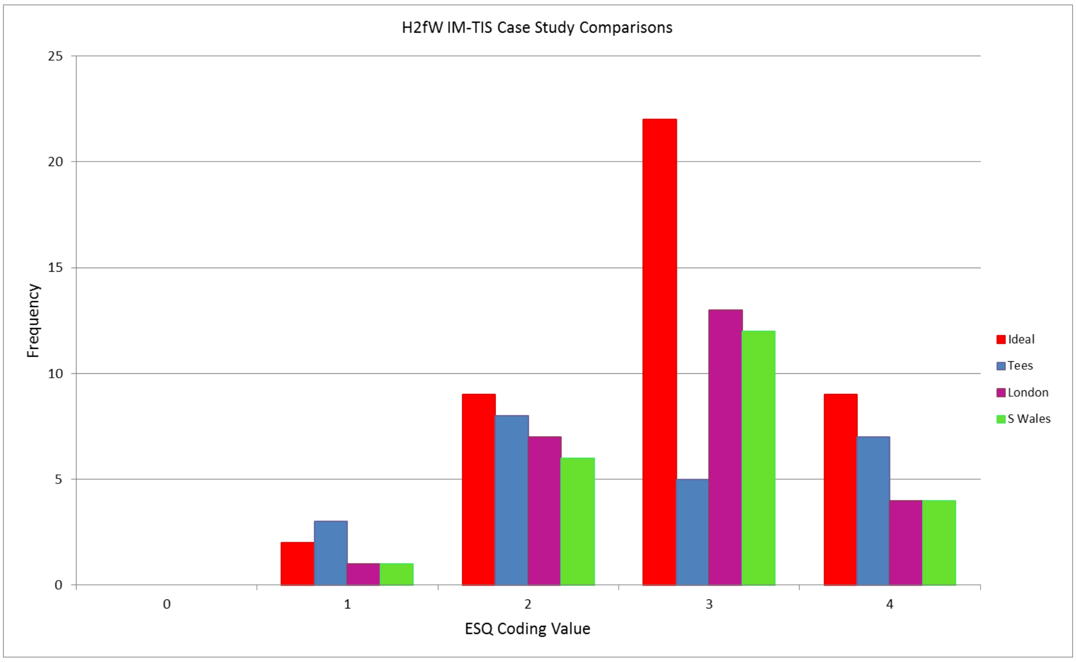


Figure 8.1. Comparison graph showing the differences between private, public sector led TIS and the original IM-TIS model.

Figure 8.1 shows that in the case of the private sector led TIS (shown in blue), there are fewer level 3 interactions than in the other three cases. The interactions that are absent are often represented by government led initiatives and activities. This is explained in detail in section 6.4.2. Additionally, Figure 8.1 shows the Tees Valley TIS having a greater number of Level 1 and level 4 interactions than London and South Wales. The Level 4 interactions described in Table 5.2 as of particular importance to successful TIS are often the business and enterprise based interactions that are harder to achieve. This is noteworthy as, even though the Tees Valley does not have the regional government support seen in South Wales and London, it is achieving the more challenging interactions. This can be seen in the overall effectiveness calculations in section 6.9. The private sector led system shows fewer Level 3 interactions than those seen in the original IM-TIS model, as well as South Wales (green) and London (purple) case studies. However, it did not demonstrate a substantial difference in the overall efficiency of this system compared with London and South Wales. This is due to the private enterprise and business related interactions having higher ESQ levels.

An interesting comparison can be made with the private sector led system described in section 6.4.2 and the illustrative worked example described in section 7.2. The private sector led TIS presented for Tees Valley is missing a number of government led relationships. These interactions represent elements of the TIS that can assist in moving towards a fully functioning and successful system. The importance of these relationships in terms of providing evidence and creating impetus for action within the TIS relates to both *Influence on the direction of the search* and *Market development*. This may suggest that should the government led relationships be activated in this type of TIS, then it may begin to resemble the original IM-TIS model system and revert to a public sector led TIS. This hypothesis, however, should be tested through further investigation over time of the IM-TIS model in the case study regions.

One consideration of any further research, to be discussed in Chapter 9, should be whether the IM-TIS model focuses too much on the role of government and academia. Adjusting the interactions may create a conceptual IM-TIS model that is a hybrid public sector and market driven system. An over reliance on government intervention may not create a sustainable business environment and it would be more appropriate for the TIS to become sustainable.

The literature review also showed in section 2.4 that the importance of the time dimension is not always recognised in the functions of innovation literature. Innovations in a technological field evolve and the monitoring of a technological innovation system should consider this. It may not be possible to create a conceptual model that is adaptive over time, because every set of interviews is a snapshot in time and cannot account for learning within the system. However, the IM-TIS offers a conceptually simple system that could be applied at regular time periods to monitor a TIS. The evidence from the application of the IM-TIS model to the three case study regions suggests that making comparisons of the changes that occur in a particular TIS over time would be straightforward. It is also suggested that the evolution of each function over time could be mapped out using repeated applications of IM-TIS. The activation of the relationships would increase the overall effectiveness of the case study regions. This would move these regional technological innovation systems closer towards the original system presented by the IM-TIS model. From this it may be suggested that the IM-TIS model represents a highly effective public sector led innovation system.

In its current format the matrix cannot be used to assess how a TIS will change over time. It is able to show how pathways may be developed to achieve a fully effective TIS. One approach to uncovering pathways to deliver policy and strategy for the production of hydrogen from waste has been described in Chapter 7 in the worked example. To fully understand the development of the TIS over time, further case study investigations in the three regions would be required. Particular attention to the different contributions from the three main sectors of academia, the state and private enterprise could provide more insight into the development of TIS for hydrogen from waste.

The suggestion that the original IM-TIS system is a public sector led system gives greater emphasis on the need to provide clear leadership from the government through policy and strategy development. The development of policies and guidance documents that promote a technological direction appears to create stronger, more efficient TIS (see section 6.9). The original IM-TIS model contains more Level 3 interactions than Level 4 or Level 2 interactions and many of these are based on government and academic based activities, as shown in Figure 5.3. The suggestion that the original IM-TIS system is a public sector led system is based on the number of government and academia interactions and the results of the London case study and worked example in section 7.2. London is the only region in the case studies that was supported by policies that explicitly mention hydrogen production from waste. The emerging TIS produced through the case study analysis in sections 6.7 & 6.8 demonstrates greater overall efficiency than Tees Valley and South Wales, and followed the system outputs of the original model. This could indicate that should the relationships continue to be activated, then the result would be a fully functioning TIS for hydrogen from waste in London. Likely outputs from such a TIS would be active programmes of hydrogen produced from waste being used in commercialised projects.

Although the original IM-TIS model is considered here to be a public sector led innovation system, the literature for functions of innovation presented by (Bergek *et* *al.* 2008) discusses the ability of a TIS to move to a situation where it is sustainable without the push-pull of government policy. In terms of the technological field for hydrogen from waste, and perhaps in other emerging renewable technologies, involvement from the state may be more important because it appears to create an environment where activities seen in the Level 3 and 4 interactions that include business and enterprise are able to occur (see Figures 5.3 & 5.4). In mature systems this would be expected; however, following this research it is proposed that in an emerging TIS the creation of positive changes through government initiatives that increase entrepreneurial activities and mobilise resources is prioritised. Emerging technological fields, such as hydrogen from waste, may ultimately reach this state, but currently require nurturing through policy direction and government initiatives. This hypothesis would need to be tested at specified time intervals to identify how the TIS changes. It would also be possible to identify specific interactions that are implemented during the time period within the TIS and, following the application of the IM-TIS model, to identify if the activity has been successful or not. This is discussed further in section 9.4 (Further Research).

8.2.1 Function Interaction and Failure

An important feature of the IM-TIS system is presented by a tightly grouped set of functions with a high level of interaction, as shown in Figure 5.6. A tightly grouped TIS (more so than the original IM-TIS) may mean that each function may be very reliant on the other functions in the TIS. This means that if one function is subordinate and grouped tightly with other variable functions it will rely heavily on the dominant functions to achieve their outputs before it can be activated. This could, for example (using the original IM-TIS model for illustrative purposes), be represented by a pilot hydrogen from waste scheme needing large capital funding from government. In this case the *Mobilise resources* function would dominate the *Influence on the direction of the search* function. This may be because a government department is waiting for the evidence to support a technology before it releases R&D funding and without that R&D funding there may be no evidence. This could lead to the system breaking down, where a lack of success in one function results in a domino effect such that failure occurs in all functions across the system. A similar problem may also become apparent when there is one function in the TIS that is ranked as very dominant. This could also lead to a system failure where the system is overly dependent on one function.

A system where functions demonstrate strength in their own right, or an ability to access their needs via an alternative pathway, could be less likely to fail due to the inaction of one function. Consequently, the original system, although tightly grouped, does not present functions that are very dominant. It may be possible to create a system where the ESQ coding is re-evaluated by a researcher, applying new levels to the model interactions; the aim here would be to reduce the tight grouping and bring more flexibility to the system. This may be useful in helping a policy maker to review the importance of particular interactions within the system and their role in achieving the postulated policy. However, the result may not be as representative of 'real' situations as seen in the application of IM-TIS.

In conclusion, this research has shown that the IM-TIS model developed for this research has been successfully used to compare three different 'real' situations. It could however, be adapted through either re-evaluation of ESQ coding or by developing new interactions between the functions. To understand how these possible changes would affect the model's reflection of real life, further case studies would have to be carried out. Thus, although successfully applied in this situation, the IM-TIS model may need further adaptations to suit other TIS applications.

8.2.2 Matrix Pathway Development

Chapter 7 presented an illustrative example using pathway development through the matrix to deliver a particular set of policy targets. In this example, the policy being considered (London Assembly 2011) had not presented any details on the *Resource mobilisation* function, so the pathways identified accounted for the lack of this function and created a route around the matrix to activate relationship interactions that promoted the delivery of the policy. It may be the case that the IM-TIS model can be used to analyse possible pathways for delivering outcomes in all sectors of business, academia and government where one or more functions may be under represented. It is suggested that the pathway approach offers a potentially useful concept for delivery of outcomes for technological advancement. This is particularly the case where the solution to galvanising action in a particular technological field is not immediately clear.

Understanding the possibilities for system failures may contribute to the development of strong and independent functions. Such functions could be strongly interactive within the technological innovation system, without the over reliance on each other that might arise. For example, successfully creating *Entrepreneurial experimentation* and pilot programmes without explicit policy leads may require greater input from *Market formation* and *Influence the direction of the search* that are not government led interactions. Increasing the strength and influence of these functions on the *Entrepreneurial experimentation* function may help to achieve a more independent non-public sector led system Recognising the need for and promoting greater independence of a TIS may prevent the disappearance of important contributions from the private sector to the development of renewable technologies, should policies change due to economic change or political pressures.

In the literature discussed in section 2.4, Bergek *et al.* (2008) apply their conceptual framework to IT developments in a care home. Their example aims to demonstrate how the framework can be used to map out the inducement and blocking mechanisms. In this example the function of *Creation of positive externalities* is not included. The only reason given for this is a decision made by the Swedish Agency for innovation systems. The evidence from the results of the IM-TIS model's application to hydrogen from waste suggests that although this function is very subordinate and responds to the activities of other functions in the system, it is vital for promoting acceptance and legitimising the system in this case. (Bergek *et al.* 2008) describe how this function includes details on:

- Emergence of pooled labour markets—this contributes to knowledge development and diffusion, and resource mobilisation. As the knowledge of a technological field grows, and acceptance and legitimation increases, so does the financial and human input into the sector.

- Emergence of specialised intermediate goods and services—growth of the supply chain. Knowledge is created, goods and services in the technological sector may be reduced, and experience is accumulated. The growth of the supply chain legitimises the technology.
- How information flows and knowledge spills over thus contributing to knowledge development and diffusion.

It is therefore suggested that the monitoring of this function, *Creation of positive externalities,* could explain some aspects of what makes a TIS successful in some situations. This may be particularly important in emerging systems for renewable energy technologies. These technologies are involved in a conflict with the incumbent fossil fuel based system. Society, as described in the policy landscape in section 2.1, is seeking a successful system that provides energy security and affordability, combined with reduced CO_2 emissions. This is in contrast to the incumbent system that offers high levels of CO_2 emissions combined with cost effectiveness from an existing global infrastructure. The *Creation of positive externalities* function may provide insight into how technologies in the renewables sector are being absorbed and accepted into the current system. Monitoring this function may show the number of new entrants into the sector, jobs created, the development of specialised and accumulated knowledge and its accessibility by non-experts. Capturing the strength of this function will enable the shift from one energy paradigm to a desired vision of a new renewables-based paradigm to be tracked as changes occur. It may also be possible, through the monitoring of this function, to understand in more detail how society learns or might be helped to learn to accept new renewable technologies and incorporate them into conventional thinking. This function, as with all the functions of innovation, will need repeated monitoring to take account of changing relationships within the TIS as technologies and TIS mature with time.

In conclusion this research has demonstrated that there are a number of reasons why TIS are either successful or not. There is, as suggested by Truffer *et al.* (2012), a need to understand the relationships between each of the functions of innovation. The IM-TIS model does this through the interactive matrix approach. The IM-TIS model has successfully shown the differences between each of the case study regions in the UK. From the case study results presented in sections 6.2–6.9, it has been possible to establish that by changing the ESQ and/or interactions within the matrix, failure within the system can be prevented. IM-TIS can be used to show a timeline for an emergent TIS through to maturity, an area not currently covered in TIS studies.

In addition to the above findings, the IM-TIS model has also, through an illustrative worked example in section 7.2, demonstrated the usefulness of mapping out the policy pathways within a TIS. The results of this have shown that, in combination with the Q methodology group identities, the relationships between the functions of innovation in the hydrogen production from waste TIS can be better understood. This investigation has shown that policies can be activated and reviewed to fit with the emerging innovation system.

8.3 Application of the IM-TIS model

A unique element of the IM-TIS methodology is the application of the model compared to previous applications of RES. The RES technique has been applied predominantly to systems where the relationships between the variables are well established, such as a construction or mechanical application. Examples of this would be in slope stability where water content of soil changes the soil characteristics or in rock engineering where fracturing in rock reduces strength (Hudson 2013). In a conventional engineering or construction based application of RES, the relationships between variables will exist, for example, water movement through rocks or the movement of a particular mineral through soil; this is the nature of these sectors. RES produces a "fixed" system in the form of the interaction matrix when applied conventionally. In the case of IM-TIS it produces an "ideal" system where it is unlikely that all interactions between the variables, in this case functions of innovation, are present. In this application of RES, in the form of the conceptual IM-TIS model, to the technological innovation system the relationships between the functions are not always clear. The relationships or interactions between the different functions have to be developed and built up around a technology. The influence of each relationship on others may be unexpectedly powerful or weak. In the case studies undertaken for this research, the dominance of R*esource mobilisation* in all three regions was evident. However, in the worked example in Chapter 7, *Resource mobilisation* was absent from government policies. The relationships required to meet the original system requirements do not necessarily exist at the beginning and may emerge and evolve over time. It is this fluidity of the IM-TIS model's application to the TIS that allows for the comparison of the different regional TIS. This may also lead to temporal issues, such as not knowing when or how the relationship may emerge; so it may become necessary to replicate the investigation in due course.

IM-TIS offers an easily accessible model that can be used by non-academic assessors who wish to know more about a particular technological innovation system. From a more detailed perspective, the manner by which ESQ coding is conducted in this application is subjective and based on the knowledge of the assessor using the IM-TIS model to understand a particular TIS; the assessor could be an individual from government, academia or business. Depending on the sector that the assessor may be from, the ESQ levels representing the importance of each interaction may vary and may be adapted to suit the needs of the organisation or individual carrying out the investigation. It is possible that this type of adaption of the model may lead to inconsistencies in the results, and will also mean that no comparison between the results of technologies examined with an adapted IM-TIS can be made with the original.

This development of ESQ coding produces the model outcomes of different levels of interactions shown in Figure 7.1. In turn, a visual identity for each regional TIS case study can be produced and this allows for an assessor to make comparisons between current TIS and future TIS. It is suggested that it can be used as both a strategic planning and research tool for government, academia or business that need to understand the technological developments in a particular sector.

8.4 The future of hydrogen from waste in a low carbon energy system in the UK

The evidence from the case studies presented in this thesis suggests that the hydrogen from waste system and market are still in an emergent state. With efficiency levels based on IM-TIS operating at around 50%, significant changes in government policy and business investment may be required to shift this technological field into the commercial phase. Notwithstanding the content of the London waste strategy (London Assembly 2011) and the work of the London Hydrogen Partnership (LHP 2010), there has been no further mention by the London Assembly of utilising hydrogen produced from waste across the UK. For this sector to flourish and contribute to a low carbon energy system in the UK there will be a growing need for renewable fuels advocacy and research and development. Continued activities that advocate further technological development and commercialisation of hydrogen from waste technologies may spark further changes in government and business commitment. Commitment through investment and partnerships between organisations in the TIS, similar to those found between Air Products and Impetus Waste in Tees Valley, may begin to build up the market for hydrogen from waste through the development of infrastructure to support an emerging market.

The methodologies applied in this research, IM-TIS and Q methodology, have not attempted to identify leading technologies for hydrogen production from waste. The generic relationships developed in the IM-TIS detail the cause and effect variability of organisational behaviour within the functions. This analysis cannot support a single technological direction, since the focus is on a technological field that encompasses all technologies that could deliver hydrogen from waste. The process conceptualises and visualises change processes and sequences of events unfolding within the function relationships. These changes and events may contribute to the expansion of the technological field. Ultimately the aim of the TIS is to diffuse and commercialise technologies for hydrogen from waste within the incumbent energy system.

The results of the case studies do not suggest that hydrogen produced from waste will be either significant or minimal within future energy systems. The case studies reveal that the current situation for hydrogen produced from waste is that it is welcomed in principle by certain actors. Conceptually, hydrogen from waste forms part of the views and perceptions of experts revealed through the application of Q methodology. However, these ideal scenarios are not yet being realised. Hydrogen produced from waste management processes remains an aspiration for our low carbon future. The work of organisations like Air Products and Impetus Waste is beginning to address these aspirations and contribute to our low carbon energy system in the UK.

8.5 Concluding Comments

In this chapter the results have been applied to gaps in the TIS studies literature. The results of this research have successfully addressed the research questions identified in the initial section of this chapter. Section 8.1 has discussed the characterisation of "*How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?"* and gone one step further to identify how these different groups may impact upon the TIS for hydrogen production from waste.

Sections 8.2 & 8.3 have discussed *What does the comparison (Aim 2) between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?*

The results have shown that the bespoke model IM-TIS developed for this research does allow for comparisons with real situations, but may still require adaptations and re-evaluation of the quantitative elements to be valuable in all situations.

Finally section 8.4 discusses *What role might hydrogen produced from waste have in a future low carbon energy system in the UK?* In this section it has been established that despite substantial aspirations for hydrogen produced from waste, the hypothesis presented in Chapter 1 "*that the arguments supporting drivers and barriers for the use of hydrogen as a fuel have not changed over the last twenty years despite the technological advancement in the field*" is correct.

The following Chapter presents this research's contribution to the academic fields, suggested further research and the thesis conclusions

8.6 References

Bergek A., Jacobsson S., Carlsson B., Lindmark S., Rickne A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (2008) 407–429

Breukers S., Hisschemöller M., Cuppen E., Suurs R. Analysing the past and exploring the future of sustainable biomass. Participatory stakeholder dialogue and technological innovation system research. Article in Press: Technological Forecasting and Social Change 2013

Hawkey D.J.C. District heating in the UK: A Technological Innovation Systems analysis. Environmental Innovation and Societal Transitions 5 (2012) 19–32

Hudson J.A. 2013. A review of Rock Engineering Systems (RES) applications over the last 20 Years. In: *Rock Characteristion, Modelling and Engineering Design Methods.* (Eds. J.A. Hudson, X.T. Feng, Tan F.): Proc. SINOROCK2013 ISRM Symposium, Shanghai, China, June 2013.

LHP 2010. London Hydrogen Action Plan 2010-2012. London Hydrogen Partnership. Greater London Authority. Accessed online May 2013 http://www.london.gov.uk/lhp/documents/LondonHydrogenActionPlan2010-12.pdf

London Assembly 2011. London's Wasted Resource: The Mayor's municipal waste strategy. 2011. Accessed online August 2013 http://www.london.gov.uk/sites/default/files/Municipal%20Waste_FINAL.pdf Greater London Authority Publication.

Negro S.O., Hekkert M.P., Smits R.E. Explaining the failure if the Dutch innovation system for biomass digestion—A functional analysis. Energy Policy 35 (2007) 925–938

Negro S.O., Suurs R.A.A., Hekkert M.P. The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system. Technological Forecasting and Social Change 75 (2008) 57–77

Nill J., Kemp R. Evolutionary approaches for sustainable innovation policies: From niche to paradigm. Research Policy 38 (2009) 668–680

Suurs R.A.A., Hekkert M.P., Kieboom S., Smits R.E.H.M. Understanding the formative stage of technological innovation system development: The case of natural gas as an automotive fuel. Energy Policy 38 (2010) 419–431

Truffer B., Markard J., Binz C., Jacobsson S. A literature review on Energy Innovation Systems. Structure of an emerging scholarly field and its future directions. Chalmers University. November 2012.

9 CONCLUSIONS AND CONTRIBUTION

In the previous chapters of this thesis the research problem was introduced and addressed. A literature review was presented to contextualise the research field and justify the need for conducting the research. The Q methodology and Rock Engineering Systems (RES) methods have been used or adapted to fulfil the aims and objectives connected to the research questions. These methods have been applied to further understand the technological innovation system (TIS) for hydrogen from waste technologies in the UK.

As presented in Chapter 1, an underlying hypothesis of this research is that by investigating the innovation system that encompasses the technologies for the production of hydrogen from waste, insight into developing, diffusing and commercialising these technologies into the incumbent energy system will be gained. The methods described in Chapter 3 were undertaken and results presented and discussed. In section 9.1 the thesis conclusions are presented, in section 9.2 suggestions for further research are made and the contributions to the academic field identified in section 9.3.

9.1 Conclusions

This doctoral research includes the first application of the Q methodology in the field of hydrogen production from waste in the UK and the new adaptation of the RES (IM-TIS) method for assessing TIS. Additionally, both applications of IM-TIS presented in this thesis are new. These applications provide a new way of analysing TIS for hydrogen production from waste and conducting policy review and assessment. The methods described above were developed in order to address the overarching research question:

- *What role might hydrogen produced from waste have in a future low carbon energy system in the UK?*

To help address the overarching question more clearly, two research sub-questions were created. The research methods were designed to answer the sub-questions, both of which are designed to contribute to addressing the overarching question:

I. How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste? And

II. What does the comparison between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?

Q methodology was applied to answer the second research sub-question and its associated objective (given in section 1.2):

- To analyse and characterise, using Q methodology, the different expert communities involved in the sustainable production of hydrogen from waste in the UK and their involvement in the technological innovation system.

Q methodology was used to reveal different identities of groups of experts working within the technological field. This method was considered most appropriate to address the first research sub-question presented above because Q methodology combines qualitative and quantitative methods to reduce researcher bias and build up stakeholder identities. Three identities were uncovered, Hydrogen from Waste Advocates, Cautionary Environmentalists and Hydrogen Technologists. The identification and classification of the identity of stakeholders provided further insight into developing the innovation system. It is concluded that the use of this methodology was appropriate and did address the research question: "*How do experts in the hydrogen from waste community view the possibilities for hydrogen produced from waste?"* The Q methodology results provided further insight into TIS actor identities and allowed for greater understanding of the behaviours of TIS actors to be developed.

The second research sub-question had four associated objectives. They are:

- <u>To develop a model</u> to analyse the technological innovation system for hydrogen from waste using an interaction matrix incorporating the results of the Q methodology.
- <u>To Identify and characterise three regional case studies</u> where hydrogen from waste activities are clustered.

- To apply the model to these regional case study zones and make key observations and recommendations for each region.
- To produce direct results for these case studies and discuss the possible implications of these results.

To assess the current situation for technologies used for the sustainable production of hydrogen from waste in the UK, the RES interaction matrix was adapted and applied to three case study regions in Tees Valley, London and South Wales. It is considered that through the development and application of the conceptual IM-TIS model that the four objectives were fulfilled in the process of delivering the case study methodology, as shown in sections 6.3–6.9.

The IM-TIS model is a combination of RES and the functions of innovation conceptual framework. IM-TIS is a new conceptual model used for considering technological innovation systems. The development of this model is indicative of a highly effective technological innovation system. The model presents forty-two possible interactions or relationships between the functions of innovation. Applied to three case study regions the technological innovation systems for hydrogen from waste were assessed.

This research successfully applied the model in two new ways that allowed existing technological innovation systems in case study regions to be assessed against the original IM-TIS outputs and regional comparisons made. The results suggest that the lower percentage effectiveness found is due to the emergent nature of TIS for hydrogen from waste.

These comparisons provided a potentially useful tool that shows the current efficiencies of a TIS as well as the elements and interactions which may require activation in order to achieve a mature TIS. This application of IM-TIS to the case study regions differed from previous applications of the RES model, which had been applied to an engineering project system where all the interactions and relationships already existed. IM-TIS showed how this new model could be used to identify interactions and relationships that do not yet exist within a TIS. It can also be used to establish the level of effectiveness at which the studied TIS is currently operating. The IM-TIS model applications indicate that the emergent systems, particularly in South

Wales and London, are following the system outputs of the cause-effect co-ordinates and rank of functions of innovation presented by the original IM-TIS model. The Tees Valley case study did not follow the original IM-TIS as clearly as the London and South Wales cases. Analysis (as described in section 6.9) indicates that all three case studies have immature systems. It is likely that they will require further support to deliver hydrogen from waste.

The IM-TIS model enabled comparisons to be made of the different regions to the original system and to each other. The results revealed two different types of innovation system in the UK, public sector led systems and private sector led systems. From this evidence it is concluded that the model did reflect 'real' situations, as both Wales and London were comparable to the IM-TIS model, albeit operating at a lower effectiveness. The results from Tees Valley did not reflect the original IM-TIS model, however they were still comparable to the original system. A situation could have occurred where none or very few of the interactions in IM-TIS were found through the qualitative case study data. If this had been found the model would not have reflected 'real' situations. It is concluded here that this application of the IM-TIS model adequately addressed the second sub-research question presented earlier: *What does the comparison (Aim 2) between 'real' and the 'model' technological innovation systems tell us about both the model and the development of regional innovation systems in the field of hydrogen production from waste?*

In a further application of the IM-TIS model, the factor identities from the Q methodology were combined with IM-TIS to illustrate how the approaches taken in this research project could influence the delivery and review of UK hydrogen from waste policies (given in section 7.1). In a worked example considering the London case study region, the characteristics of the factor identities supported particular actions in particular functions of the TIS to deliver policy ambitions. Attributes associated with particular identities could also be considered to provide some explanation for behaviour exhibited by organisations within the technological innovation system. The worked example demonstrated the usefulness of IM-TIS as an assistive tool in delivering and reviewing policies for hydrogen from waste.

So, in answer to the overall research question, the evidence from this research showed that it is likely that hydrogen from waste may have a role in the transport sector. The hydrogen used for transport could be produced from waste as part of a decentralised system. This conclusion is based on the policy direction that is reflected in the London case study and the illustrative worked example in Chapters 6 and 7 respectively. In addition to this, the Q methodology produced identities of groups that were supportive of the automotive industry and the further development of fuel cells. These groups were the Hydrogen from Waste Advocates and Hydrogen Technologists, described in detail in Chapter 4. Further to this, perceptions of the future applications for hydrogen from waste were elucidated in the forty-eight interviews undertaken in this research. The results of the Q methodology have identified hydrogen from waste as a potentially desirable component of a low carbon future, according to the actors identified and consulted. However, the contribution that hydrogen from waste may make to a future low carbon energy system cannot be quantified from this research, but from the Q methodology and the IM-TIS case studies, it is concluded that there is a need for firm direction in policy making to promote hydrogen from waste production and use.

Finally, the application of the IM-TIS model to the case study regions identified the *Resource mobilisation* function as the most important function to deliver successful hydrogen from waste technologies. It is considered from this research to be key in driving hydrogen from waste technologies to commercialisation and developing greater “buy-in” from all sectors. It is suggested that improving and developing this function of innovation would provide the greatest impact to make hydrogen production from waste a reality.

9.1.1 Study Limitations

The limitations of these studies were primarily temporal, in that the Q methodology results and case studies provide a snapshot in time of the regionally based TIS for hydrogen from waste in the UK. To obtain a picture of how the TIS may change over time, repeated applications of the methods would need to be undertaken. It is concluded that further applications of these methodologies would continue to provide constructive insight into the growth and build-up of the technological innovation system for hydrogen from waste in the UK. The time constraints faced by Q methodology were based around the identities. The identities produced by the Q methodology reflect who the experts participating were and how the expert participants understood the technological field at that time. Results were unable to account for participant learning as technologies and knowledge advances with time. The IM-TIS case study analysis of the emerging technological innovation systems also represented a snap shot of the situation in the regions at that time. The case studies could not account for developments in each function of innovation that may occur within the technological innovation systems over time.

9.2 Suggested further research

The Q methodology and IM-TIS methods applied in this research project produced qualitative data. For the Q methodology, twelve initial expert interviews were conducted to produce evidence for the concourse. This was followed by the digital audio recording of a further twenty-five Q-sorts that recorded the thoughts of the experts as they undertook the Q survey. This included seven of the twelve who participated in the concourse interviews. The case studies produced ten in-depth interviews from organisations involved in the production of hydrogen from waste in the case study regions. This is a total of forty-seven interviews that ranged from twenty minutes to one and a half hours in length. These were recorded and transcribed. The qualitative data obtained here has been utilised for particular components of the Q methodology and to identify and visualise the existence of relationships within the IM-TIS model. Furthermore, the interview data has informed the construction of factor identities in the Q methodology and provided some reasoning behind the level of influence functions have on each other in the IM-TIS model.

Two main areas of further research are suggested:

First, in addition to the analyses described above, the data may offer new information and detail about the perceptions and expectations of the individuals interviewed as part of this doctoral research. Thus, it may be possible for the data to be further analysed to look for more evidence of the barriers and drivers that are in operation in the regions. An important aspect of this research was that at the time no commercial projects were in operation in any of the case study regions. The qualitative data may provide further insights into why investment in projects has not been forthcoming since that time. It is suggested that the analysis of this data using alternative qualitative analysis methods would be suitable for further research. This further research could include event analysis or an analysis of the barriers and drivers for the hydrogen from waste TIS. This may provide added depth to the results found in this research and explain why particular interactions in IM-TIS did not occur or why particular actors behave in a certain way.

The further analysis of the qualitative data could potentially lead to a repeat of the Q methodology in the case study regions to further assess the role of actors within these regions. In this research, the Q methodology included participants from the UK technological innovation system for hydrogen from waste, rather than just from the case study regions. The wider geographical focus of the Q methodology has been recognised as a limitation to the combining of methods to further develop the IM-TIS in the regions. This is because a Q methodology specific to the regions would have supported the application of the IM-TIS model in terms of policy assessment and review, as seen in Chapter 7. A regionally specific Q methodology would have given insight into the experts working in the regions and not across the UK. Carrying out this process may enhance understanding of why particular relationships between functions struggle to manifest in specific regions.

The second main area for further research relates to the further development of the IM-TIS model for use with specific technologies. The model presented in this research focuses on generic relationships expected within a technological innovation system. It may be possible to further analyse more technology-specific relationships in association with the qualitative data obtained through interviews. The interviews may support the development of technologically based relationships along with the existing generic ones. This may lead to more technology focussed functions and may result in a deeper understanding of the functions' impact on specific technologies. Further adaptations of the IM-TIS model for other technologies in different sectors could then follow.

Researching specific technologies, such as fuel cells, may assist in developing systems that promote virtuous cycles of innovation (Hekkert *et al*. 2007). A virtuous cycle is a process of change that promotes positive feedback loops that strengthen and build up to the creation of positive destruction in the incumbent system. Positive destruction is a movement of innovation that is considered good for society and the planet and breaks down the incumbent system. This is the type of movement that innovation in the renewable energy sector seeks to achieve. The virtuous cycle can be countered by vicious cycles of innovation. It is described as a situation where negative fulfilment of functions may reduce the effectiveness of the TIS and result in stopping progress (Hekkert *et al.* 2007). In this research it was not felt that determining the virtuous and vicious cycles within the TIS could be analysed to a sufficiently high standard. It was felt that more information about why the functions were behaving in particular ways would be required. It was not considered possible to obtain this information in the allotted timeframe and therefore may be suitable for further research. In addition to the virtuous and vicious cycles described in the literature, consideration must be given to cycles that create unexpected consequences within the TIS and wider environs. Consequences could be positive or detrimental to another sector or community; it is proposed that another area for further research would aim to understand the role of the TIS for hydrogen from waste in terms of virtuous, vicious and unexpected cycles and the relationships of the TIS in a broader context.

A final area for further research would be to address the temporal issues associated with this research identified in section 9.1. The aim here would be to understand how TIS change and evolve over time. To this end, the case studies could be replicated in the future, perhaps at an interval of five to ten years. From this it may be possible to demonstrate how the relationships in the IM-TIS model are initiated and changed over time. This type of analysis may lead to identification of further differences and similarities between the two typologies of public and private sector led TIS.

9.3 Contribution

In this section the contribution this doctoral research has made to the academic fields is identified. This thesis contributes to two main strands of academic research. The first is the socio-technical elements of hydrogen production from waste and the second is in technological innovation systems.

First the contributions to the socio-technical component of hydrogen production from waste:

1. The application of Q-methodology, a form of discourse analysis in this field. This has identified three identities exhibited by experts working in the national innovation system for hydrogen production from waste. This new understanding of the actors involved in the innovation system supports further development of the hydrogen from wastes in the UK.
2. Development of the supporting IM-TIS model, that can assist policy makers in making decisions on new policy or reviewing the effectiveness of existing policies for hydrogen from waste in the UK. This is a new adapted model with a new application.
3. An analysis of the technological innovation system in three regions of the UK. This has provided details of regional activities associated with hydrogen production from waste and the effectiveness of these activities in terms of a technological innovation systems approach. These analyses have been compared, providing new insight into the way hydrogen from waste is developing across the UK. The mapping and comparison of hydrogen production from waste activities across the UK has not previously been investigated.

The second academic strand where contributions have been made is in innovation systems, specifically functions of innovation within technological innovation systems.

Development of a new technological innovation systems model, IM-TIS, that combines existing models of functions of innovation and (RES). This is an adapted model that is applied to a fluid system. In terms of the existing RES methodology, this is also a new application.

In this chapter the conclusions of this doctoral research have been given, opportunities for further research discussed and the contribution to two different academic fields identified.

9.4 References and Bibliography

Hekkert M.P., Suurs R.A.A., Negro S.O., Kuhlmann S., Smits R.E.H.H. Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change 74 (2007) 413–432

10 Appendix 1: Details of Digital Portfolio (CD attached to Thesis)

1. Q methodology raw data
2. RES-TIS matrix
3. RES-TIS ESQ matrix

11 Appendix 2: Data Collection (as per confidentiality agreement)

Table 11.1 Organisations involved in Q methodology concourse development

Organisation	Position	Date
Air Products	Commercial Manager	May 2011
Aston University	Head of EBRI	June 2011
Cardiff University	Research Associate	April 2011
Energy Saving Trust	European Funding Manager	May 2011
Energy Technologies Institute	Energy from waste specialist	June 2011
Independent Consultant	Chemical Engineer	May 2011
Leeds University	Research Manager	May 2011
St Andrews	Research Manager	May 2011
UCL	Research Associate	June 2011
Welsh Government	Waste Strategy Advisor	June 2011
WRAP	Commercial and industrial waste account lead	April 2011

Table 11.2 Q sorts all undertaken between March and June 2012

Organisation	**Sector**
AEA (energy)	Industry
AEA (waste)	Industry
AEA (biomass)	Industry
AEA (energy from waste)	Industry
AFC Energy	Industry
Air Products	Industry
Cardiff University	Academic
Cardiff University	Academic
DECC	Government
EA Wales	Regulator
Environment Agency	Government
EST	Industry
Glamorgan University	Academic
Independent	Industry
Leeds University	Academic
Leeds University	Academic
Planet Hydrogen	NGO
St Andrews University	Academic
St Andrews University	Academic
WAG	Government
WAG	Government
WAG	Government
Welsh Automotive Forum	Industry
WRAP	Industry

Table 11.3 In-depth interviews for case studies

Organisation	Position	Date
Air Products	Commercial Manager	August 2012
Croydon borough	Waste Manager	August 2012
EA Wales	Waste Advisor	September 2012
Element Energy	Consultant	September 2012
GLA/ LHP	Head of Waste	August 2012
Glamorgan University	Researcher	August 2012
Imperial College	Research Associate	August 2012
Impetus waste	Commercial Manager	September 2012
SITA UK	Plant Manager	August 2012
Wales Automotive forum	CEO	August 2012