Mapping innovation and diffusion of hydrogen fuel cell technologies: Evidence from the UK's hydrogen fuel cell technological innovation system, 1954-2012

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Abstract

With the global sustainability transition in energy, hydrogen fuel cell (HFC) applications currently have important niche roles to play across several industrial sectors. Theorists examining this innovative activity have identified key socio-technical factors affecting the nature and pace of change. One functional approach to innovation, Technology-Specific Innovation Systems (TSISs), places national HFC Technological Innovation Systems (TISs) within a framework of a global HFC TSIS. This analytical approach suggests that HFC innovation can start anywhere in space. However, in a case study of HFC innovation and diffusion in the UK covering sixty years' activity, this theoretical assumption is challenged. Event history analysis and interviews using a neofunctionalist TSIS approach suggest that positive feedback was on the brink of occurring in the UK HFC TIS by 2012. When additional organisational and spatial indicators are added, the evidence on the ground does not support the aspatial assumptions that underlie TIS heuristic thinking. Rather, it suggested that type of investment funding and spatial location can influence HFC innovation. In this context, the implications for HFC policy in the UK are discussed.

Keywords: hydrogen fuel cells; innovation; UK; sustainability; TSIS; spatial

1.0 Introduction

Globally, there are numerous challenges to the sustainability of economic activity in all industrial sectors (Stern, 2006, Delina, 2017). In terms of the supply of energy, sustainability issues include the depletion of natural resources, increased local air, land and water pollution and the contribution to rising amounts of greenhouse gases (GHGs). Atmospheric carbon dioxide (CO_2) levels have now put the Earth's climate system into "dangerous territory" (Miller, 2018). From the 1990s, research and development (R&D) into disruptive energy storage technologies, such as hydrogen fuel cells (HFCs), became more urgent. HFCs store and release electrical energy cleanly and on demand (Appleby, 1990, Hart, 2000, Hardman et al., 2013). When installed in stationary and mobile devices, advocates claim HFCs have the potential to help regional, national and international policy makers decarbonize and move away from fossil fuels (Walsh, 1990, Perry and Fuller, 2002, Bockris, 2002, Eliasson and Bossel, 2002, Hall and Kerr, 2003, Agnolucci, 2007, Maggio et al., 2019, Staffell et al., 2019, Pollet et al., 2019). HFC development in the last two decades continues to face the key issues of making unit costs competitive (Zegers, 2006, McDowall and Eames, 2007, Agnolucci and Ekins, 2007), the mixed public understanding of the potential (Haraldsson et al., 2006, Ricci et al., 2008, Martin et al., 2009, Bellaby et al., 2016), slow shifts in market demand (Ajanovic and Haas, 2018), the means of improved public-private coordination (McDowall, 2012) and the level of commitment of major manufacturers to this radical technology (van den Hoed, 2005). However, the reasons why HFC innovative activity might take off in one country, region or locality and not in another are not well understood by academics (Tanner, 2014, Tanner, 2016). The research reported in this paper addresses this issue.

Innovation Studies' (IS) researchers have long analysed the institutional reasons for 'developmental gaps' to help explain uneven development and national 'catching up' policies (Lundvall, 1992, Freeman, 1987, Dosi et al., 1988). One strand of IS theorizing focuses on technologies. It includes a number of heuristics: 'Technological Systems' (TSs), 'Technological Innovation Systems' (TISs) and 'Technology-specific Innovation Systems' (TSISs) (Carlsson, 1997, Carlsson et al., 2002, Hekkert et al., 2007). TSIS advocates claim that universal functional mechanisms in a national TIS are the causal agents of sustainable change (Geels, 2010). Further, this technological strand of IS thinking suggests innovation can take place anywhere in space via actors' universal ease of access to resources from so-called 'global technological opportunity sets' (Carlsson, 1997). Critics suggest that the TSIS heuristic risks overemphasizing the causal explanations for innovation (Coenen and Díaz López, 2010, Coenen et al., 2012, Coenen and Truffer, 2012). The key socio-technical processes, they claim, are more likely grounded in place-dependent activity linked to institutional structures. Socio-economic concepts of space and place, it is suggested, should be incorporated into these heuristics. Related theoretical concerns include: 1) the reliance on aggregating micro-level data to the meso- and macro-levels, 2) the lack of a regional 'container' for analysis, and 3) the lack of predictive powers (Hacking, 2017). Such theoretical concerns suggest that the TSIS approach may underplay the co-evolution of emerging innovations and existing regimes and so fail to effectively address structural change (Geels, 2010).

The results of the Supergen XIV Delivery of Sustainable Hydrogen ('DoSH') project (Metcalfe et al., 2008) (see Acknowledgements) cast some doubt on the potential efficacy of the TSIS approach. The DoSH research suggests that the organisational and spatial dimensions of HFC innovative activity need fuller consideration when using the TSIS approach to innovation with renewable energy (especially when aligning theory with policy) (cf. Hacking and Eames, 2012, Contestabile et al., 2013). This article's analysis and conclusions address these points of critique.

Ultimately, this article builds on both the TSIS approach and the DoSH project's analysis. It investigates further whether HFC innovation and diffusion are affected by types of funding arrangement and spatial location. Section 2.0 of the paper describes the methods used to extend and update the DoSH datasets. Section 3.0 further details TSIS theory. Results and analysis are presented in Section 4.0. Conclusions and a research agenda are set out in Section 5.0.

2.0 Methods

The justification for using the TSIS approach to innovation is two-fold: technological transitions typically take a long time to occur (Sovacool and Geels, 2016), and certain social processes like cumulative causation, path creation, path dependence and 'lock in' are suspected to be at work (cf. Myrdal and Sitohang, 1957, Garud and Karnoe, 2013, Grabher, 1993).

The mixed-methods design used here involves a number of analytical steps, three datasets and various outputs (Figure 1). The design was informed by the TSIS approach (Hekkert et al., 2007) with its seven innovation system functions (Table 1) interlinked by feedback loops (possible feedback loops are shown in Figure 2). Theoretical concerns highlighted by the DoSH study suggest additional codes could be added to the TSIS event data. These are: 1) organisational (for public, private or public-private funds) and, 2) spatial location.

Figure 1: Research Design with three Datasets (A, B and C) and a Range of Outputs

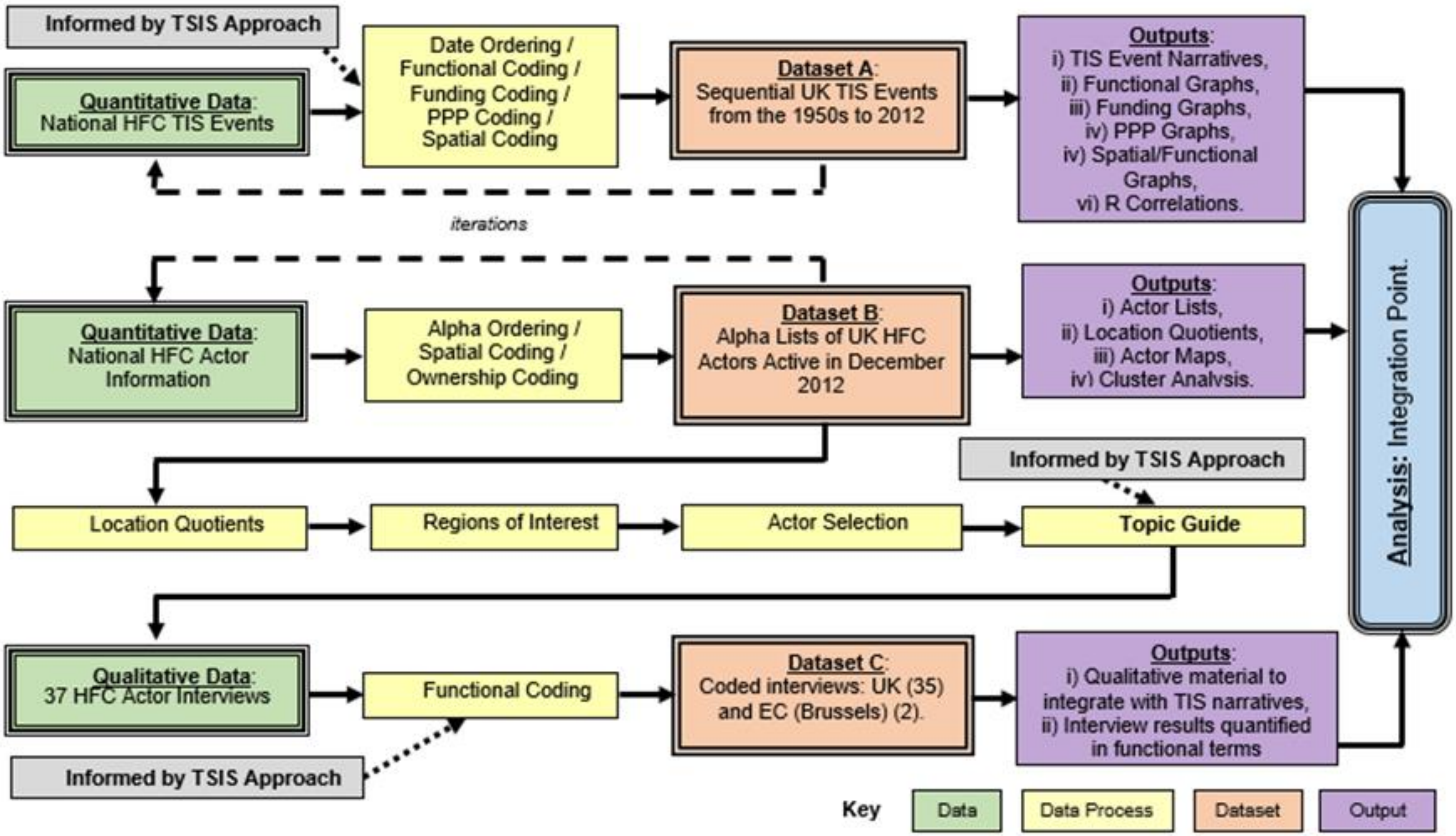
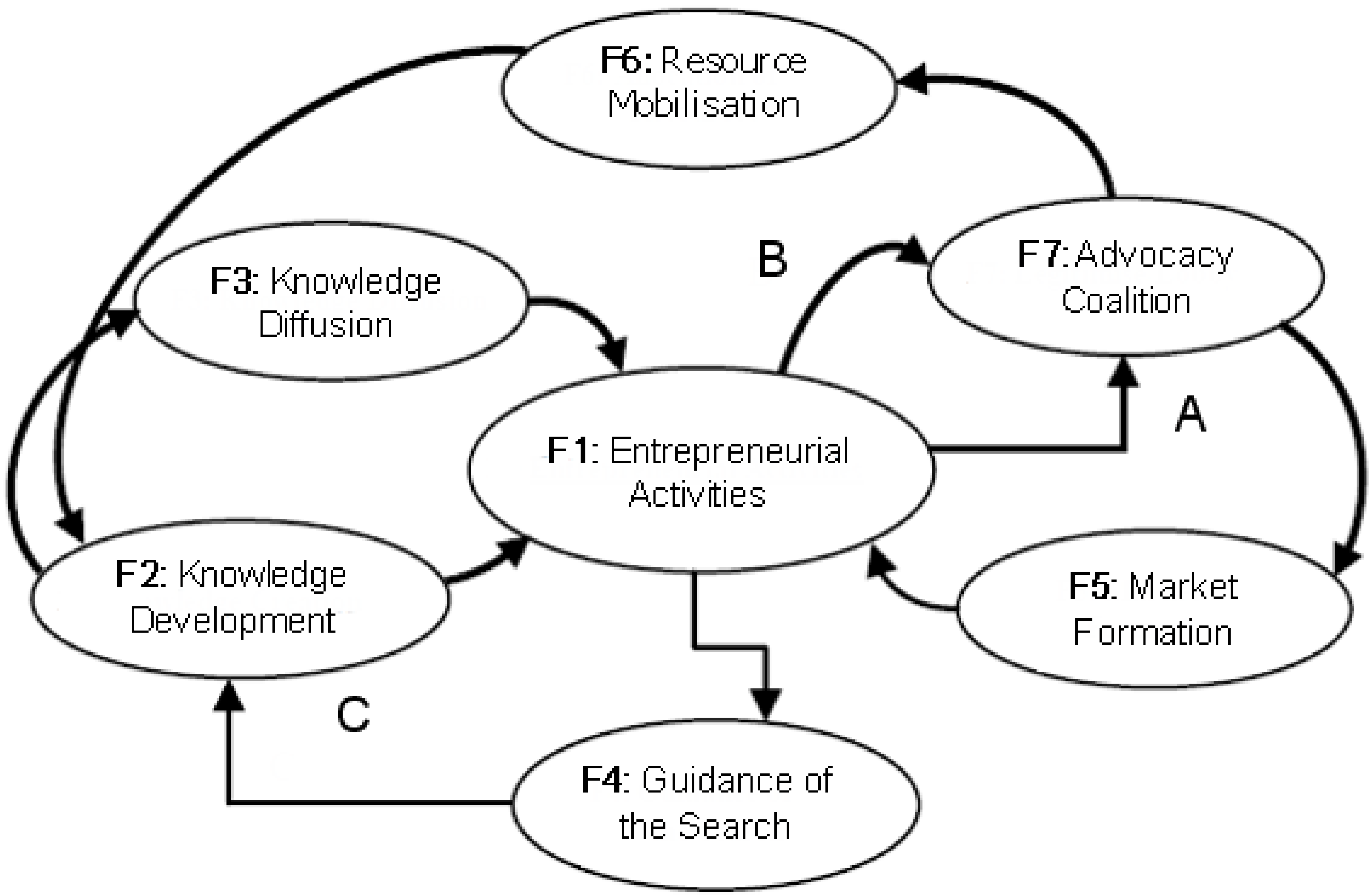


Table 1: Generic TSIS Functions (For Renewable Energy Innovation)

System Functions	**Event category**	**Value**
Function 1: Entrepreneurial activities	Project started	+1
	Contractors provide turn-key technology	+1
	Project stopped	-1
	Lack of contractors	-1
Function 2: Knowledge development	Desktop-, assessment-, feasibility studies, reports, R&D projects, patents	+1
Function 3: Knowledge diffusion	Conferences, workshops, platforms	+1
Function 4: Guidance of the search	Positive expectations of renewable energies;	+1
	Positive regulations by government on renewable energies;	+1
	Negative expectations of renewable energies;	-1
	Negative regulations by government on renewable energies	-1
Function 5: Market formation	Positive expectations of renewable energies;	+1
	Positive regulations by government on renewable energies;	+1
	Negative expectations of renewable energies;	-1
	Negative regulations by government on renewable energies	-1
Function 6: Resource mobilisation	Subsidies, investments Expressed lack of subsidies, investments	+1
		-1
Function 7: Advocacy coalition	Lobby by agents to improve technical, institutional & financial conditions for technology	+1
	Expressed lack of lobby by agents;	−1
	Lobby for other technology that competes with particular technology;	−1
	Resistance to change by neighbours (NIMBY attitude)	−1

source: Hekkert and Negro (2009)



source: Hekkert et al, (2007)

Figure 2: TSIS Configuration with Example Feedback Loops (A, B and C)

Figure 1 shows key outputs (in purple) from this methodology include:

- quantitative UK-wide HFC TIS event narratives presented as timelines,
- quantitative HFC actor lists of corporate and academic research centres, and
- qualitative interview material.

The sub-sections below give more detail about definitions and methods employed to collect, code and analyse this data.

2.1 Definitions

Innovation is of key interest to practitioners and academic researchers across a range of business and management disciplines because of its role in sustainable economic growth. It is inevitably a contested concept that is not susceptible to a single, agreed definition. Freeman (1974) avers that innovation involves the technical, design, manufacturing, management and commercial activities used in the marketing of a new, or improved, product or the first use of a new, or improved manufacturing process or equipment. Van de Ven et al. (2000, 32, emphasis in original) define innovation in terms of its measurement as delineated 'events' at the micro scale:

> "*Innovation* is … the introduction of a new idea, the *process of innovation* refers to the temporal sequence of events that occur as people interact with others to develop and implement their innovative ideas within an institutional context.

Ultimately, academic researchers recognise that the transdisciplinary nature of 'innovation' offers a means of classifying different types of innovations on the basis of whether they: "bring forward something new or improve an existing aspect of the organization (nature). Similarly, innovations may be classified as product, service, process or technical (type), and the resources or means used to drive and support innovation can be identified in respect of the balance of technology, ideas, inventions, creativity, and market (means)" (Baregheh et al., 2009, 1335) (for the means explored in this study, see Section 3.0). Elements of all three of these definitions are used below.

2.2 Quantitative Data Collection Procedure

Event History Analysis (EHA) is an approach that can reveal distinct qualitative changes in innovation events over time. Allison (1984, 9) argues that: "*event history* data … [is] a longitudinal record of when events happened to a sample of individuals or collectives … [It] should … include data on possible explanatory variables”. Abell (1984, 310) explains three ways in which secondary source material is compiled and analysed in EHA:

1. The context-specific action(s) which brought the events about must be described to explain why a sequence of events occurs in terms of agency,
2. Description and explanation of other actions, by the same or other actors, which gave rise to the sequence of events is needed,
3. In writing a narrative comprising a set of interrelated actions, an explanation of the original event/sequence is given.

Hekkert et al. (2007) use a modified version of EHA based on Van de Ven’s work which aggregates event data to the macro level. This offers a picture of innovative activity at the national TIS level. By contrast, Van de Ven et al. (2000), follow innovators at the project level.

Hekkert et al.’s (2007) approach to EHA is used here to produce a UK TIS event narrative, however, modifications are made (see sub-sections 2.5, 3.2 and 3.3). A dataset of 844 events was placed on a timeline covering 1954 to 2012. The starting point marks the year that British innovator Francis ‘Tom’ Bacon filed several influential HFC patents. 2012 marked the end of the DoSH study period. Three industrial sectors - defence, transport and stationary power – emerged with transport having the greatest total number of events. Transport therefore became the leading sector to focus on.

Half of the TIS events were sourced from *Fuel Cells Bulletin* (FCB) a journal launched in 1998. Search terms included ‘UK’, ‘United Kingdom’, ‘Britain’, ‘England’, ‘Scotland’ and ‘Wales’. During an unfolding transition, it can be hard to determine which events will be significant later on. Events were therefore selected without privileging known later developments. Other events came from patent searches via the *World Intellectual Property Organization* and the US Patent Office. Search words were ‘fuel cell’ and ‘hydrogen’. Successful filings were recorded by an application’s initial filing date. Further secondary sources were: 1) academic, 2) grey literature, 3) historical, 4) state policy, 5) university, and 6) web pages. The HFC TIS narrative was created by analysing the spreadsheet, interview material and secondary sources. Where possible, events were cross-referenced to increase confidence and coherence in the narrative. Bias/contestation in the source material was overtly recognised. The UK is one of several leading nations undertaking HFC RD&D - including the US, Germany, Japan and South Korea - and this may have led to potential evidential bias. Nevertheless, the distinctly lower numbers of events prior to the 1990s compared to afterwards is clear.

From the event data, overall assessments were made of whether or not one or more ‘motors of sustainable change’ (Suurs and Hekkert, 2012) have been in evidence in the UK HFC TIS over time (see Section 3.0 for more on TSIS theory). The key challenge for coding data in this way is to ensure that the coding frame is balanced, i.e. sufficiently broad to cover all major activity but not so broad as to become unwieldy in analysis.

2.3 Qualitative Data Collection Procedure

Semi-structured in-depth interviews were conducted using a topic guide based on the TSIS’s seven system functions (Figure 3). Participants were contacted by email and phone. Interviews were undertaken by phone and in person at workplaces between March 2011 and December 2012. Participants gave audio interviews which were transcribed and coded. In interview, participants were asked what they considered the enablers of and barriers to ‘healthy’ HFC innovative activity were (Figure 3). Discussion centred on expectations for HFCs and how these are shaped by institutions, structures, processes and the uneven distribution of resources. Interviewees also spoke of their networked connections at a variety of levels (cf. Hodson et al., 2008).

2.4 TSIS Coding

A unique HFC coding frame based on Table 1 was produced (Table 2). TIS event activities were dated and coded with a TSIS function (F1 to F7; Figure 4). Each event was coded +1, -1 or 0 if, at the time, it was perceived as a ‘positive’, ‘negative’ or a ‘null’ contribution to innovation and/or diffusion within the UK HFC TIS (cf. Hekkert and Negro, 2009).

2.5 Extended Coding

TIS coding was extended to cover events’ organisational funding (yellow codes; Figure 4). This helps identify whether HFC innovation and diffusion are affected by TIS event ownership. Codes included an event’s funding status - public, private or public-private - and, with public-private partnerships (PPPs), the specific PPP approach, i.e. public leverage, contracting out, joint venturing or strategic partnering (based on a PPP typology outlined in Appendix A).

Additional codes for events’ geographical locations were added: postcode, town, city, region and

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Supergen XIV 'Delivery of Sustainable Hydrogen'

WP 4.2 - H-Delivery - Topic Guide for Participants

Date: Oct 11-Dec 12

Author: N Hacking

Note: The interview questions are all designed to reveal individuals' perceptions about the strengths and weaknesses of the national/regional innovation systems of the UK with respect to hydrogen. As such there are no wrong answers.

Topics

I am interested in who or what you feel determines the direction of hydrogen research and development in Europe. This can include the management of expectations.

I would like to know what you feel about knowledge creation and its protection.

I will ask you about the networks you are in terms of learning, knowledge diffusion and the support you draw from them.

I am keen to know what you feel about the appraisal of hydrogen in terms of environmental, social and economic sustainability.

I'll ask about the importance of mobilising resources in terms of research funding.

I am also interested in how you regard facilitating the formation of new markets.

I will ask you about the importance of having an advocacy coalition for hydrogen and also how you regard the role of the investigator/entrepreneur in terms of making things happen.

I'll ask what you think the barriers to innovation are and how to overcome them.

Lastly, we'll talk about the role of public and private research funding with respect to boosting national/regional innovation systems (and hydrogen's role therein).

Figure 3: Topic Guide

Table 2: HFC Event Coding Frame (Authors' design)

System functions	Event category	Value
Function 1: Entrepreneurial activities	Commercial HFC project started/product distributor signed/order made/product delivery made/product available;	+1
	Components/resources (supply chain) agreement made;	+1
	HFC product/demonstration started/planned/distributor signed/order or training made/service agreement;	+1
	Public and/or private demonstration of HFC applications;	+1
	HFC product standards approval;	+1
	HFC portfolio expansion/office/merger/production site opening;	+1
	HFC portfolio divestment/office closing;	-1
	HFC product/demonstration stopped;	-1
	Commercial HFC project stopped/distributor lost/orders cancelled.	-1
Function 2: Knowledge development	Desktop-, assessment-, feasibility studies, reports;	+1
	HFC R&D project started/continues (includes prototyping, lab/field trials, pilots);	+1
	HFC-related patent(s) granted/licensed/sold;	+1
	Patent expires;	-1
	HFC R&D project stopped.	-1
Function 3: Knowledge diffusion	Formation of HFC-specific conferences, workshops, platforms, professional networks;	+1
	Signing MOU / VA agreement on HFC R&D (also includes subsequent partner addition);	+1
	Termination of MOU / VA agreement (also includes partner withdrawal);	-1
	Termination of HFC-specific conferences, workshops, platforms, professional networks.	-1
Function 4: Guidance of the search	Energy regulations/policy targets that encourage the development of the HFC TIS;	+1
	Environmental and safety standards that help to guide HFC R&D;	+1
	Positive expectations/promises/roadmaps of HFC technologies;	+1
	Negative expectations/promises/roadmaps of HFC technologies;	−1
	Expressed lack of environmental and safety standards;	−1
	Expressed lack of energy regulations/policy targets.	−1

Function 5: **Market formation**	HFC-specific market instruments: e.g. feed-in rates, tax exemptions;	+1
	Corporate/state commitment to higher HFC production volumes;	+1
	Actor/network(s) agree(s) coordination/market/service standards;	+1
	Signing/extending MOU / VA agreement on HFC infrastructure (includes subsequent partner addition);	+1
	Termination of MOU / VA infrastructure agreement (also includes partner withdrawal);	-1
	HFC product passes comparative benchmark (e.g. range), environmental and/or safety standards;	+1
	Expressed lack of corporate/state commitment to higher HFC production volumes;	-1
	Expressed lack of HFC-specific market instruments.	-1
Function 6: **Resource mobilisation**	State subsidies/investor; private/long-term/'angel' investments;	+1
	Access to a skilled workforce	+1
	Access to material factors;	+1
	Expressed lack of access to material factors;	-1
	Expressed lack of access to a skilled workforce and material factors;	-1
	Expressed lack of state subsidies, private investments, long-term/angel investments.	-1
Function 7: **Advocacy coalition**	Lobbying by agents to improve technical, institutional & financial conditions for HFCs;	+1
	Expressed lack of lobbying by agents;	−1
	Lobbying for other technology that competes with HFCs;	−1
	Resistance to change - competing industry and/or project/prototype neighbours (NIMBYism).	−1

1007	Year	Even	Cumu	Date	Mo	Da	F	Function Cod	Functio	Event	Actor 1
1008	2012	1.00	706				1	Entrepreneurial /	Public and/or pri		Hydrogenesis
1009	2012	1.00	707				1	Entrepreneurial /	Public an	FRG	ITM Power plc
1010	2012	1.00	708				1	Entrepreneurial /	Public an	YH	ITM Power plc
1011	2012	1.00	709	22/03/2012	Mar	22	2	Knowledge Deve	patent	Suprar	Airbus Operations L
1012	2012	1.00	710	29/04/2012	Apr	29	2	Knowledge Deve	patent	Suprar	LGT Advanced Tech
1013	2012	1.00	711		May		2	Knowledge Deve	Report	SCO	Aberdeen City and S
1014	2012	1.00	712	28/08/2012	Aug	28	2	Knowledge Deve	patent	Suprar	Intelligent Energy Lin
1015	2012	1.00	713	14/09/2012	Sep	14	2	Knowledge Deve	patent	Suprar	SURFACE INNOVA
1016	2012	1.00	714	20/09/2012	Sep	20	2	Knowledge Deve	patent	Suprar	INTELLIGENT ENEI
1017	2012	1.00	715	21/09/2012	Sep	21	2	Knowledge Deve	patent	Suprar	INTELLIGENT ENEI
1018	2012	1.00	716	28/09/2012	Sep	28	2	Knowledge Deve	patent	Suprar	CERES INTELLECT
1019	2012	1.00	717		Oct		2	Knowledge Deve	Desk Stu	UK	Carbon Trust
1020	2012	1.00	718	17/10/2012	Oct	17	2	Knowledge Deve	patent	Suprar	Johnson Matthey F
1021	2012	1.00	719	24/10/2012	Oct	24	2	Knowledge Deve	patent	Suprar	JOHNSON MATTH
1022	2012	1.00	720	02/11/2012	Nov	2	2	Knowledge Deve	patent	Suprar	Intelligent Energy Lin
1023	2012	1.00	721	08/11/2012	Nov	8	2	Knowledge Deve	patent	Suprar	Rolls-Royce, PLC /
1024	2012	1.00	722	08/11/2012	Nov	8	2	Knowledge Deve	patent	Suprar	Rolls-Royce, PLC /
1025	2012	1.00	723	08/11/2012	Nov	8	2	Knowledge Deve	patent	Suprar	Ilika Technologies L
1026	2012	1.00	724				2	Knowlegde Deve	Demonstration		Hydrogenesis
1027	2012	1.00	725				2	Knowlegde Deve	Demonst	FRG	ITM Power plc
1028	2012	1.00	726				2	Knowlegde Deve	Demonst	YH	ITM Power plc
1029	2012	1.00	727				2	Knowlegde Deve	Demonst	SE	ITM Power plc
1030	2012	1.00	728	10/12/2012	Dec	10	2	Knowledge Deve	patent	Suprar	AFC Energy plc / Ba
1031	2012	1.00	729	19/12/2012	Dec	19	2	Knowledge Deve	patent	Suprar	Intelligent Energy Lin
1032	2012	1.00	730		Jan		3	Knowledge Diffu	Signing M	UK	Various public bodie
1033	2012	1.00	731	20/07/2012	Jul	20	3	Knowledge diffu	Signing M	Global	EC
1034	2012	1.00	732		Sep		3	Knowledge diffu	Formatio	Global	Greater Manchester

r 1 Re	Actor 1 Pl	r 2 Re	Actor 2 P	Actor 3 R	Actor 3 P	Public/Priva	PPP category
SW	Bristol					Private	-
YH	Sheffield					Private	-
YH	Sheffield					Private	-
SW	Bristol					Private	-
SE	Tunbridge Wells					Private	-
SCO	Aberdeen					PPP	Strategic Partnering
EM	Loughborough					Private	-
SE	Abingdon					Private	-
EM	Loughborough					Private	-
EM	Loughborough					Private	-
SE	Horsham					Private	-
LON	SE1					Public	-
SW	Swindon					Private	-
SW	Swindon					Private	-
EM	Loughborough					Private	-
EM	Derby					Private	-
EM	Derby					Private	-
SE	Chilworth					Private	-
SW	Bristol					Private	-
YH	Sheffield					Private	-
YH	Sheffield					Private	-
YH	Sheffield					Private	-
SE	Cranleigh					Private	-
EM	Loughborough					Private	-
LON	SW1	Global				PPP	Strategic Partnering
EU	Brussels	EM	Loughborou	SE	Walton-on	PPP	Strategic Partnering
NW	Manchester					PPP	Strategic Partnering

– TIS Codes: i) positive/negative & ii) functions 1 to 7

— Extended Codes II: Location

— Extended Codes I: Funding

Figure 4: Examples of TIS Event Coding

'external' (green codes in Figure 4). The external category covered landscape-level events affecting all nations in the global HFC TSIS, e.g. an oil embargo.

The next section discusses in more detail how the TSIS heuristic was modified and used with this particular UK HFC case study.

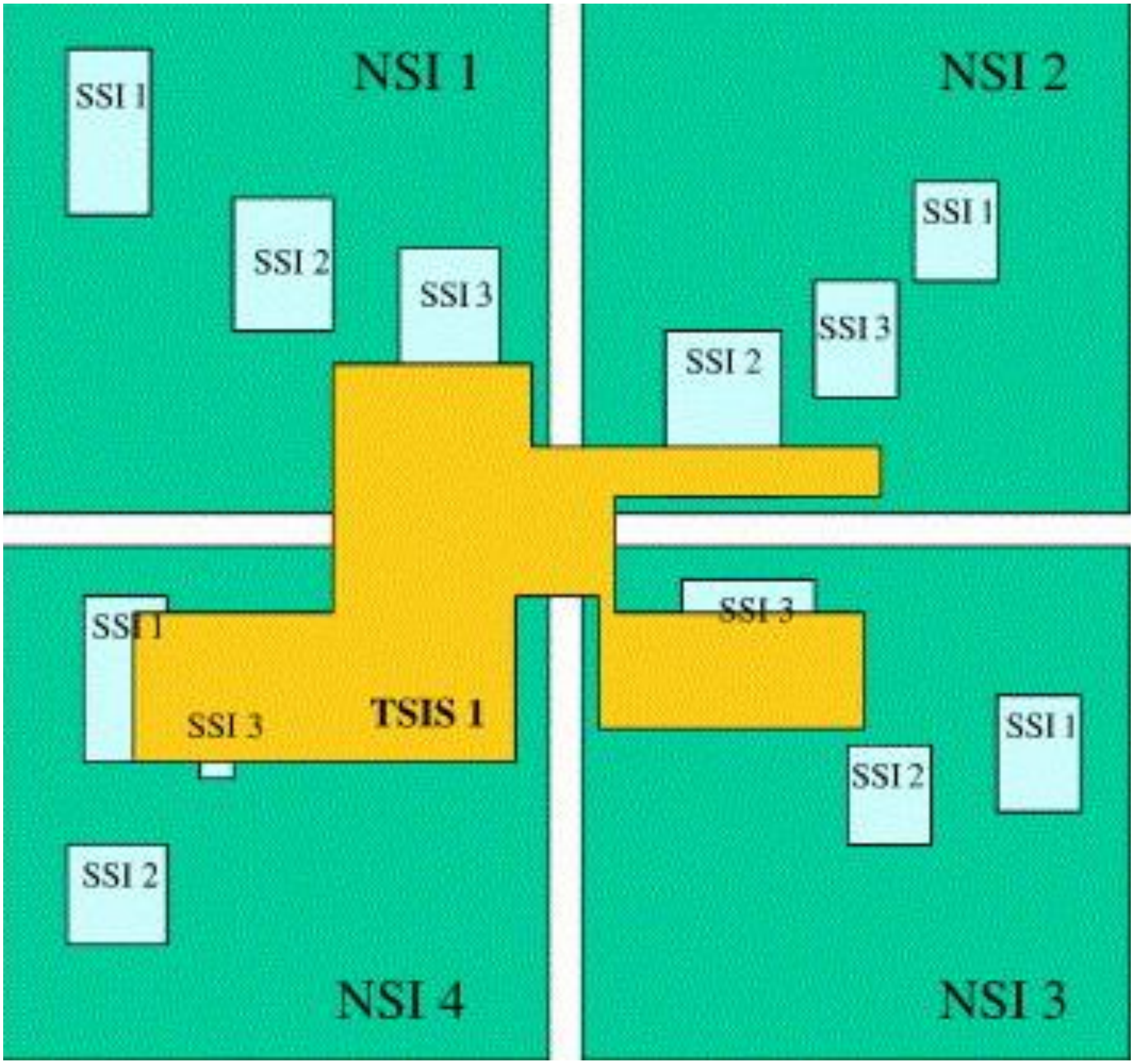
3.0 Theory

This section covers more detail about critiques of the TSIS heuristic's neofunctional ontology. In particular, the impact of space and place is negated (Coenen et al, 2012). These critiques help to make the case for more indicators to be added to the model. These extended codes cover the nature of the relationship between an event's entrepreneur and its funder as well as where an event takes place (Hacking, 2017).

3.1 TSIS Theory

The issues surrounding the timing and location of innovation are considered important by a wide range of governance actors because of the links between innovation and economic growth. With the TSIS approach, a specific technology provides the level of analysis. For that technology, TSIS advocates anticipate witnessing a temporal evolution of a system of innovation and diffusion components with each exhibiting positive feedback. As suggested in Figure 5, the TSIS's global technological system approach "cuts through both … geographical and … sectoral dimensions" (Hekkert et al., 2007, 416). A global innovation system ('TSIS 1'), shown in yellow in Figure 5, overlaps with several countries' national systems of innovation ('NSIs'), shown in dark green. The elements of the NSIs focused on HFC research are sectoral (the 'sectoral systems of innovation', or 'SSIs') shown in light green. The global diffusion of HFC innovations depends on a range of national *and* regional policy regimes stimulating HFC adoption. However, Hekkert et al (2007) do not overtly theorize how or why each system functions in certain ways at each level of activity. In particular, the impact of space and place is negated from sectors: SSIs are simply 'embedded' within the NSIs. Such an approach runs counter to known localised processes linked to uneven development, like path dependence, which help to maintain the existence of SSIs in very particular locales/regions.

With Hekkert et al's (2007) TSIS heuristic, any technological system's functional 'performance' can be scrutinized quasi-quantitatively by determining the nature of virtuous (positive) or vicious (negative) feedback loops. Such loops between functions only work in certain combinations.



based on: Hekkert et al (2007, 417)

Acronym	***Innovation System Title***	***Descending Levels of Activity***
TSIS 1	**Technology Specific Innovation System**	**Supranational/Global**
NSI 1,2,3,4	**National Systems of Innovation**	**National**
SSI 1,2,3	**Sectoral Systems of Innovation**	**[Effectively Local/Regional]**

Figure 5: Boundary relations between National, Sectoral, and Technology Specific Innovation Systems

Suurs and Hekkert (2012) suggest a typology of four ‘motors of sustainable change’. These motors characterise the functional evolution of innovative activity of a technology from early R&D through to marketplace sales:

1) a Science and Technology Push (STP) Motor (Figure 6),
2) an Entrepreneurial Motor (Figure 7),
3) a System Building Motor (Figure 8), and
4) a Market Motor (Figure 9).

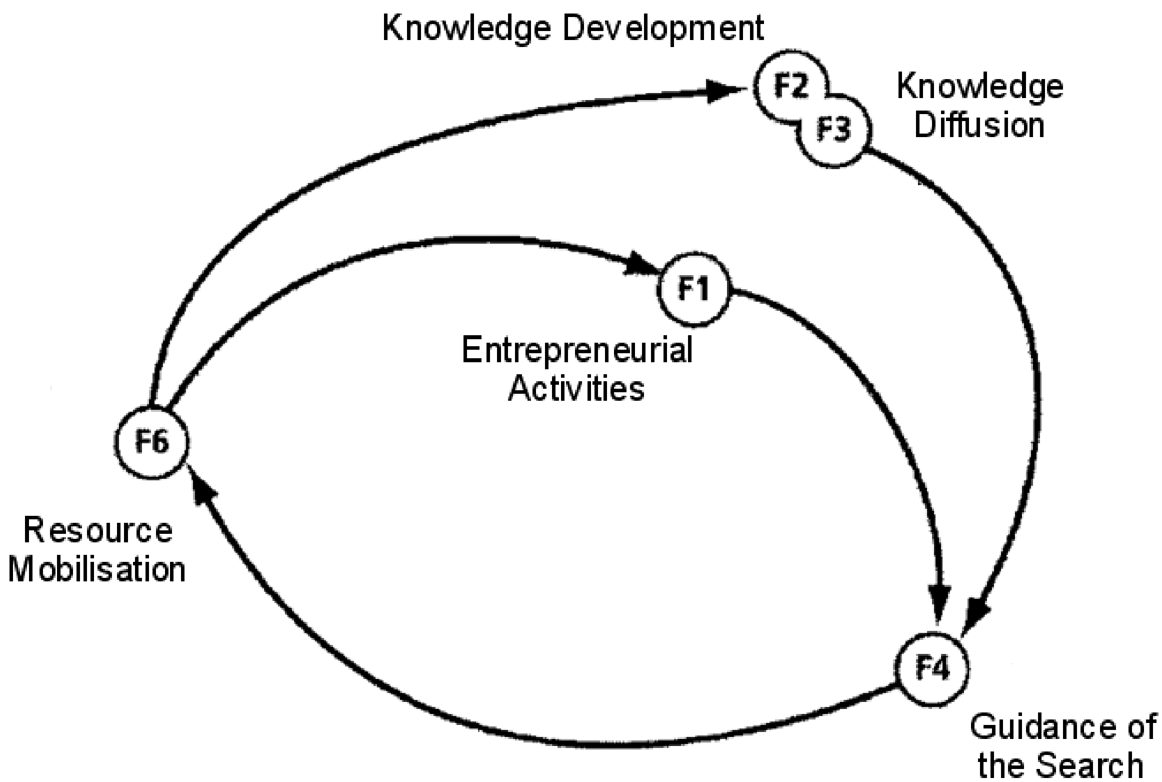
Each motor has a different combination of system functions (F1 to F7). Structural drivers and barriers within the national TIS contribute to the emergence, resilience and decline in each motor’s activity. External events at the socio-economic landscape level impact upon this schema (Suurs and Hekkert, 2012), as the Results and Analysis section reveals.

3.2 Extended Coding I - Organizational Funding

In terms of conceptions of agency and structure, there is a trade-off to be had with the TSIS’s neofunctionalist methodology. Analytical gains from the analysis of aggregated data may be outweighed by potential losses in terms of finer-grained understandings of the socio-technical processes at work at the micro-level (cf. Van de Ven et al., 1999, Poole et al., 2000). The latter involves underplaying the importance of the relative power relations of actors and individuals in networks (cf. Avelino and Rotmans, 2009, Geels, 2011) who are involved in contestations over technological choices at key technological ‘branching points’ (Foxon et al., 2013). With aggregated data, key epistemological concerns include, for example, “What is the relationship between individual [actors’] cognition and collective cognition?” and “How do firms ‘think’?” (Fagerberg, 2003, 152). In an attempt to reduce this uncertainty, coding is extended here for each TIS event to cover the organizational funding status of projects (see next sub-section). This coding covers ownership, whether public, private or public-private, which helps to assess actors’ relative agency via an indication of the nature and strength of their networked power relations, data which can be cross-referenced with interviews.

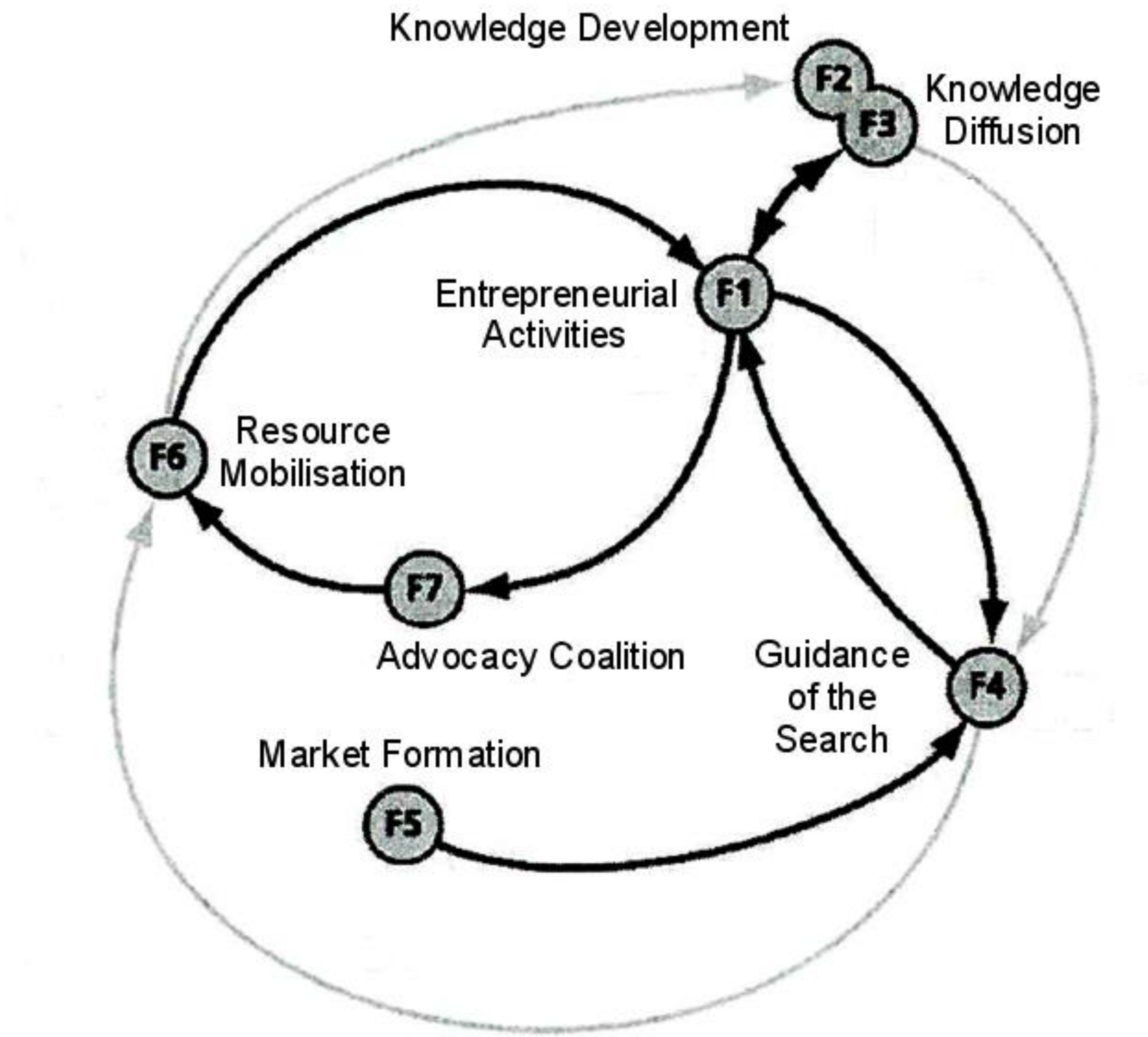
3.2.1 Role of the Public Sector in Innovation

Public private partnerships (PPPs) are an increasingly popular new environmental policy instrument which act as an approach to neoliberal environmental governance (cf. Rodrik, 2013, Mazzucato, 2013). State actors wanting to become more pro-actively involved in supporting



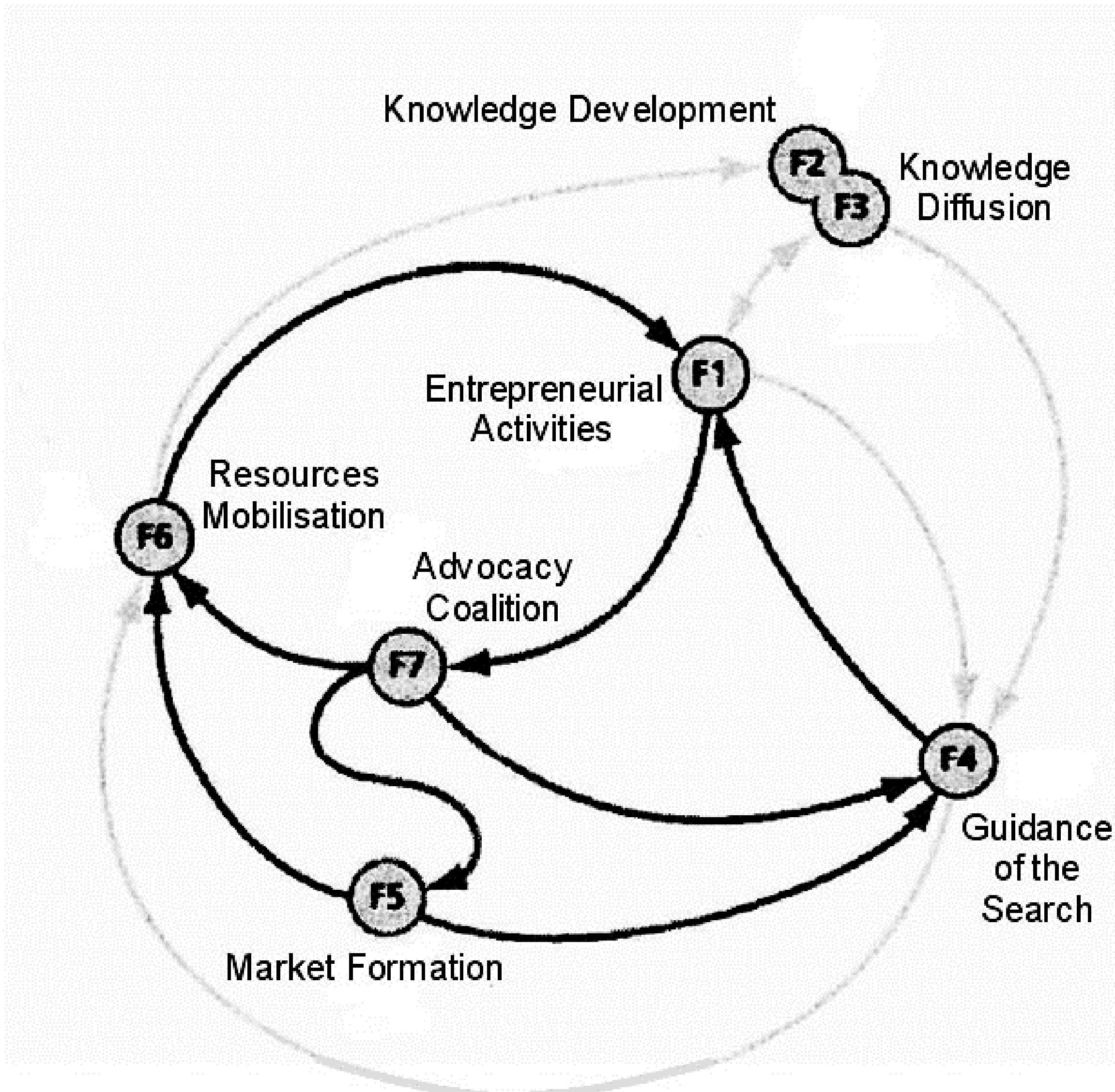
source: Suurs and Hekkert (2012, 161)

Figure 6: Science and Technology Push (STP) Motor of Sustainable Change



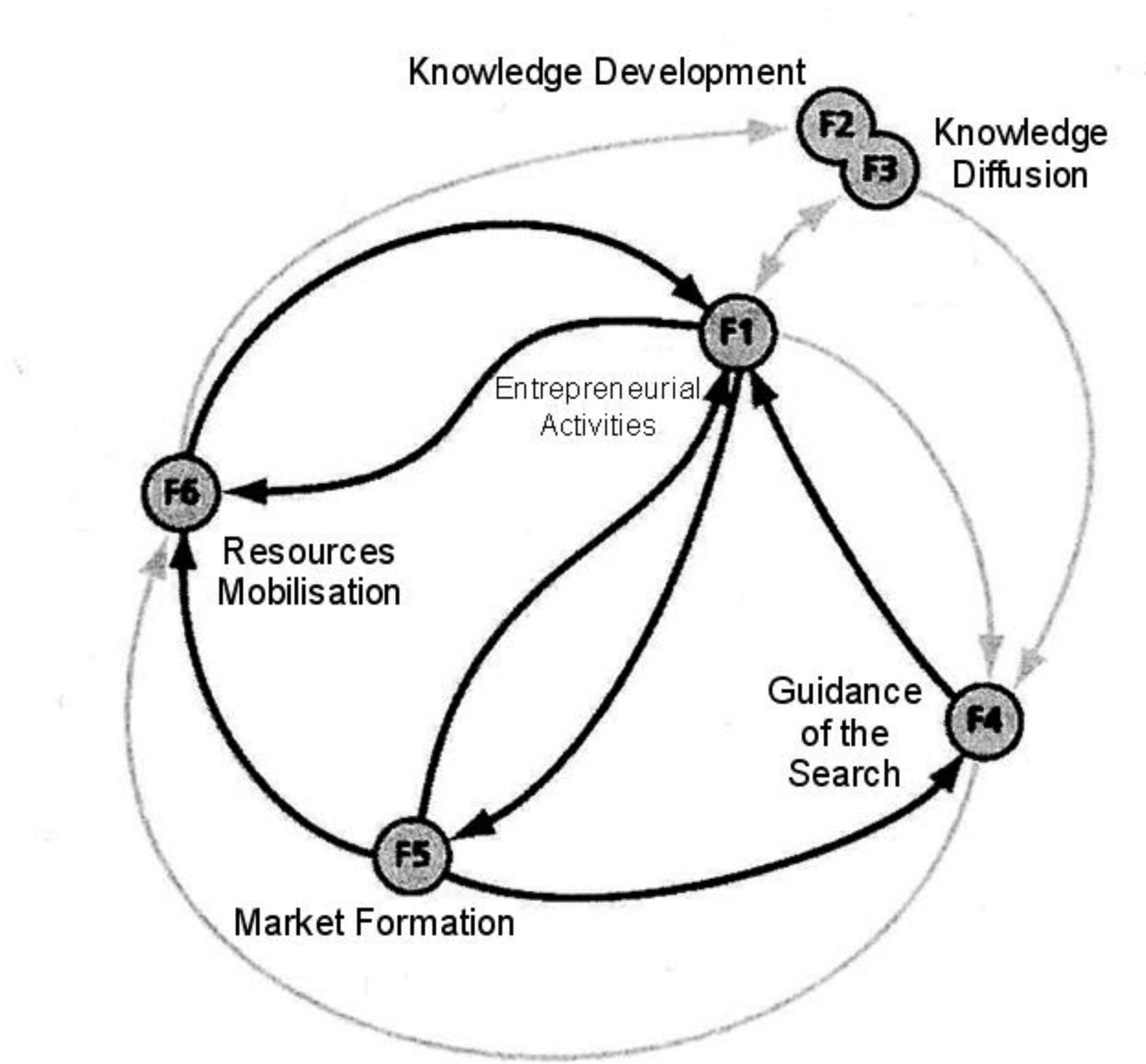
source: Suurs and Hekkert (2012, 164)

Figure 7: Entrepreneurial Motor of Sustainable Change



source: Suurs and Hekkert (2012, 168)

Figure 8: System Building Motor of Sustainable Change



source: Suurs and Hekkert (2012, 171)

Figure 9: Market Motor of Sustainable Change

RD&D for cleaner technologies can ensure reduced exposure to the financial risks involved (cf. Hodge and Greve, 2005, Verhoest et al., 2015). The EPSRC Supergen XIV DoSH data reveals a steady rise in numbers of HFC PPPs from the mid-1990s. This suggests that the types of organisational funding outlined below are a useful indicator of actors' agency, i.e. the ability to drive sustainable change (cf. McDowall, 2012).

The empirical evidence on HFC activity from the UK suggests that there are four main forms of RD&D for cleaner technologies that can ensure reduced exposure to the financial risks involved (cf. Hodge and Greve, 2005, Verhoest et al., 2015).

The four main forms of public-private activity identified empirically are:

- Public leverage – measures include funding patents and attracting actors to invest in regional sites/clusters, e.g. business parks, university science parks, and enterprise zones, where knowledge spillovers are hoped for (cf. Mans et al., 2008).

- Contracting-out - measures are designed to support investment in RD&D in energy supply and its infrastructure. Examples include contracts and contract payments for energy generation in deregulated energy markets.

- Joint ventures – JVs are typically undertaken for a very specific HFC RD&D project, marketable application or infrastructure project, and

- strategic partnering – this is in evidence where private JV actors (who may also be benefitting from public leveraging) are encouraged to become involved in the delivery of state policy objectives.

Coding along these lines impacts accordingly on the analysis of HFC innovation in the UK HFC TIS (see Sections 4 and 5).

3.3 Extended Coding II - Geographical Location

In terms of concerns regarding agency and structure, neofunctionalist approaches like the TSIS suggest that the social system itself is the causal agent of change (Geels, 2010). The TSIS approach uses a modified form of EHA to suggest causation between events. This means that the occurrence of event Y implies the occurrence of an earlier event X (Hekkert et al, 2007). However, as Kern (2012) indicates, this is not formal causation as TSIS proponents claim (cf. Coventry, 2006). Coenen et al. (2012) argue that, in fact, the TSIS heuristic risks overemphasizing apparently universal functional mechanisms as causal explanations for innovation. The key socio-technical processes at work over time, they point out, are grounded in real, *place-dependent* actor activity linked to institutional structures. In an attempt to reduce such uncertainty about causation, coding is extended here for each TIS event to cover the spatial dimensions of innovative activity so that improved spatio-temporal understandings of the causality of HFC innovation and diffusion might arise (cf. Coenen et al., 2012). Additional coding for geographical location permits analysis of dynamic change with HFC activity in these spatial contexts, particularly at the regional level which is not currently operationalized as a 'container' of analysis in the TSIS heuristic (see 'SSIs' in Figure 5).

3.3.1 Varieties of Capitalism Approach

Beyond the impact of place-specific geographies of TIS activity such as knowledge overspills in and around clusters of firms, there can be distinct national (and regional) differences in the ways capitalism is practiced (Hall and Soskice, 2001, Mikler, 2009, Nieuwenhuis and Wells, 2015). The UK, as a liberal market economy, is similar to the United States, Canada, Australia, New Zealand and Ireland, for example. It has a history of firms coordinating their activities via hierarchies and market mechanisms and has a predominantly market-centred PPP approach (cf. Lember et al., 2014). The UK has developed considerable experience with the use of PPPs thanks to its neoliberal political and economic consensus. As Nieuwenhuis and Wells (2015, 12) suggest:

> "even if there is a process of global economic integration … the outcomes are not uniform or indeed simply predictable … [T]o some degree firms are embedded in their localities, in the cultural and social practices that surround them, and in the institutional, legal and regulatory frameworks that may be more or less specific to place".

While the Varieties of Capitalism approach has been critiqued for its relatively narrow focus on institutions (e.g. Jessop, 2014), such spatial differences in governance are returned to in the analysis and conclusions in Sections 4 and 5.

4.0 Results and Analysis

In this section, the broad evolution of the UK HFC TIS is given along with detail of a specific sub-sector: automobility. Upswings and downswings in global HFC events are contextualised in terms of four Gartner-style 'hype cycles' (Bakker, 2010) which have been experienced by a number of different countries in the global HFC TSIS, but at slightly different times and with different intensities. In the case of the UK, for example, a global HFC hype cycle between 1974 and 1983 – 'hype B' – had little effect due to institutionalised energy policies, as shown below.

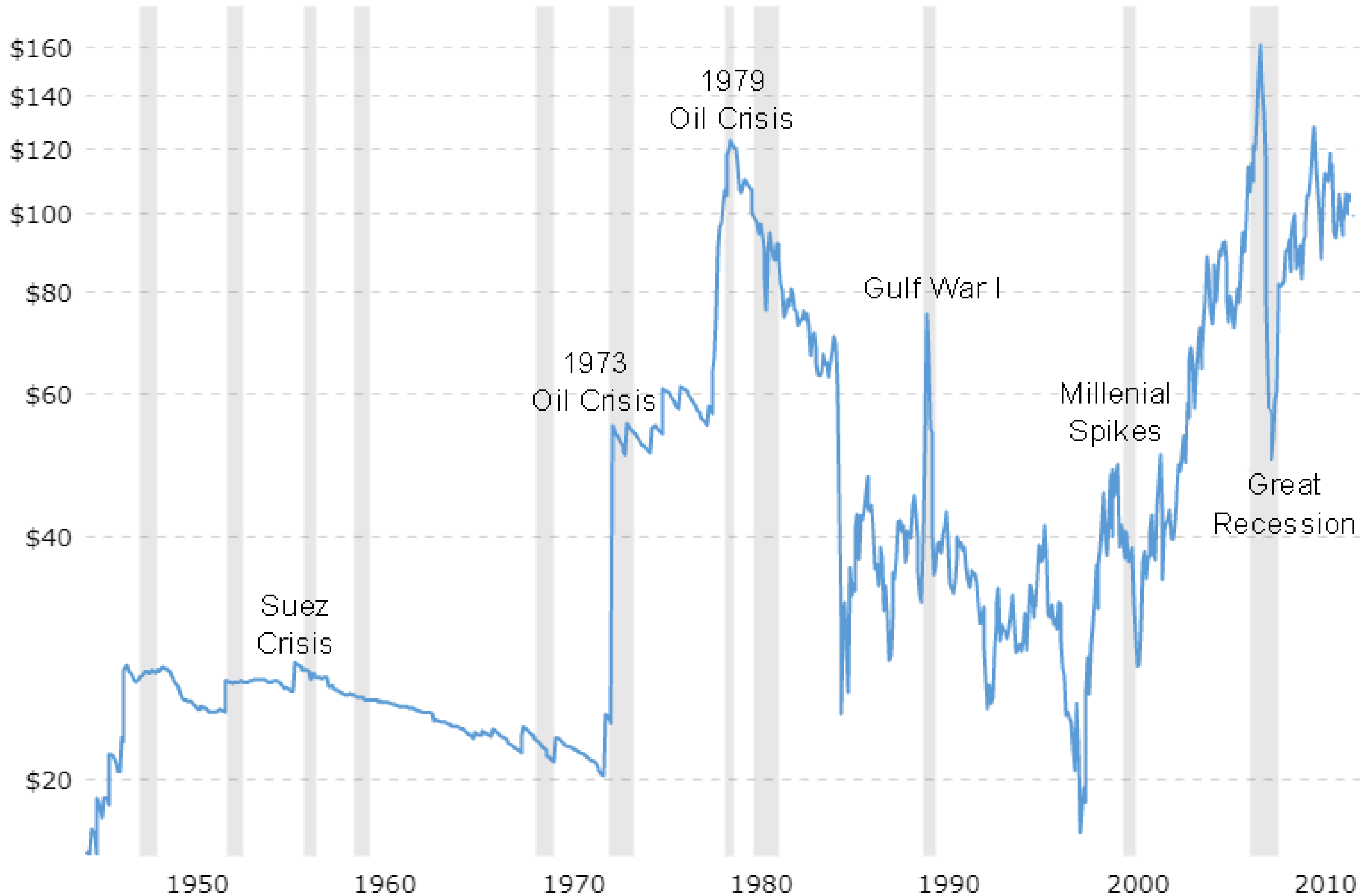
4.1 Institutional Characterisation of the UK HFC TIS

In the 1950s, the UK's regulation of energy, industry and the environment became increasingly coordinated (Appendix B). External events were as significant as internal ones. In 1956, for example, Egypt nationalized the Suez Canal depriving Britain of 80% of its crude oil from the Middle East (Bamberg, 2000) (for all external oil shocks see Figure 10). Energy security became Whitehall's top priority motivating support chiefly for nuclear R&D. The early development of the UK HFC TIS largely centred on a small handful of individual and institutional actors.

4.1.1 Global Hype Cycle A and Tom Bacon

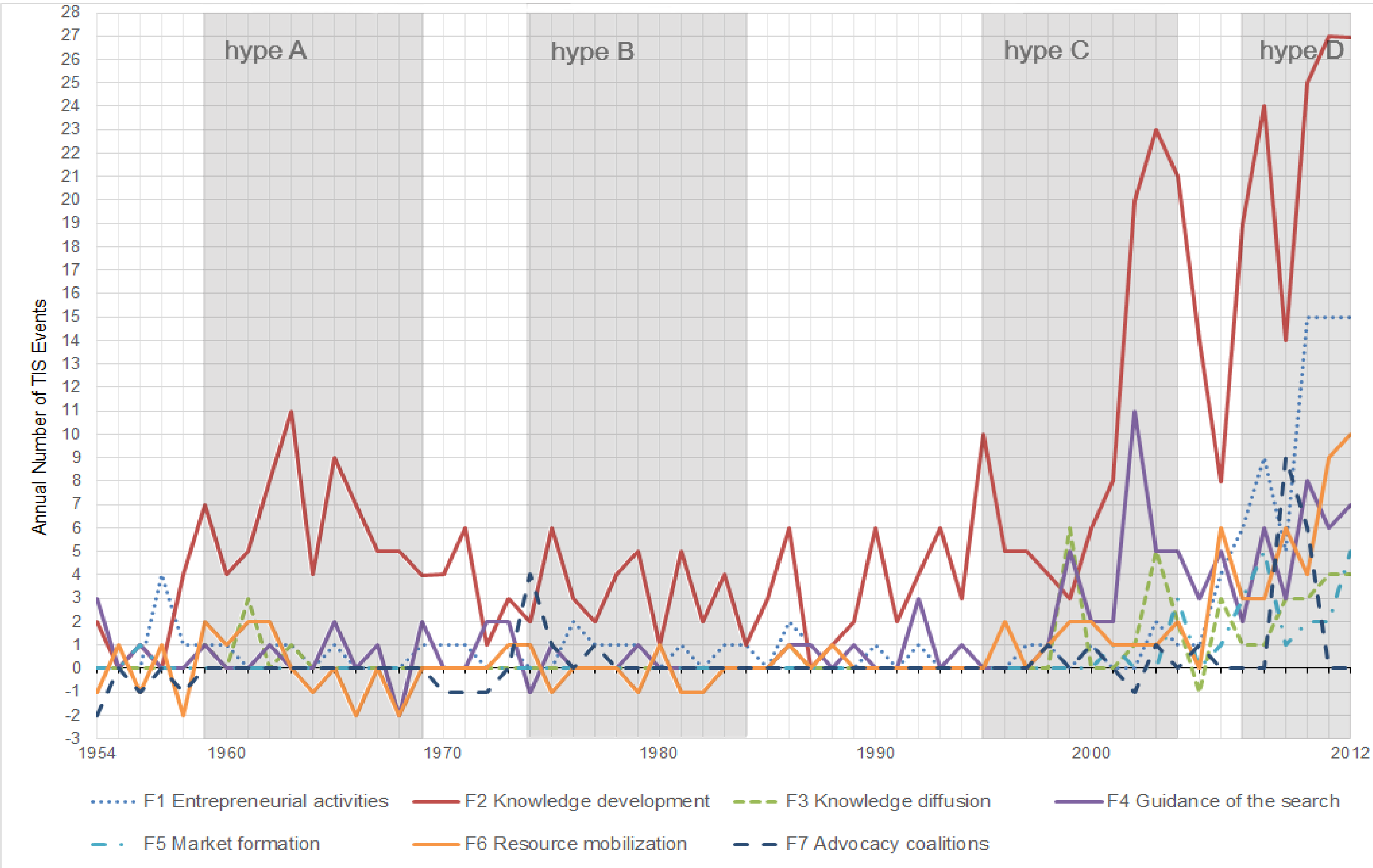
Francis 'Tom' Bacon was a Cambridge-based engineer who successfully updated the work of Sir William Grove, the inventor of the fuel cell. In 1842, the Grove Cell produced electricity via electrochemical reactions in both sulfuric and nitric acid (the latter produces toxic nitric oxide). Bacon found a safer alkaline design, the 'Bacon Cell'. He patented it in 1954 and developed prototypes for stationary power and automobility applications. Bacon's alkaline fuel cell (AFC) patents were licensed to NASA in 1959 (via some support from the UK government). The Bacon Cell assisted life support technology in the US manned spaceflight programme. This activity kick-started an upswing in global 'hydrogen hype' (i.e. positive expectations) from the early 1960s until a downswing in the early 1970s (see 'hype A' in Figures 11 and 12 and data in Appendices C and D). A few small networks of privately-backed innovators with deep pockets were spurred on by Bacon's research. Niche HFC publicly-leveraged public-private partnerships (PPPs) were also initiated via the government's National Research Development Corporation (e.g. Energy Conversion Ltd – see mention in Appendix A) after Whitehall felt that the negotiations with NASA had overly favoured the Americans.

During hype A, there was some limited functional diversity in the early HFC TIS. Entrepreneurial activity (F1) peaked at four events in 1957 (Figure 11; Appendix C). Knowledge development (F2)



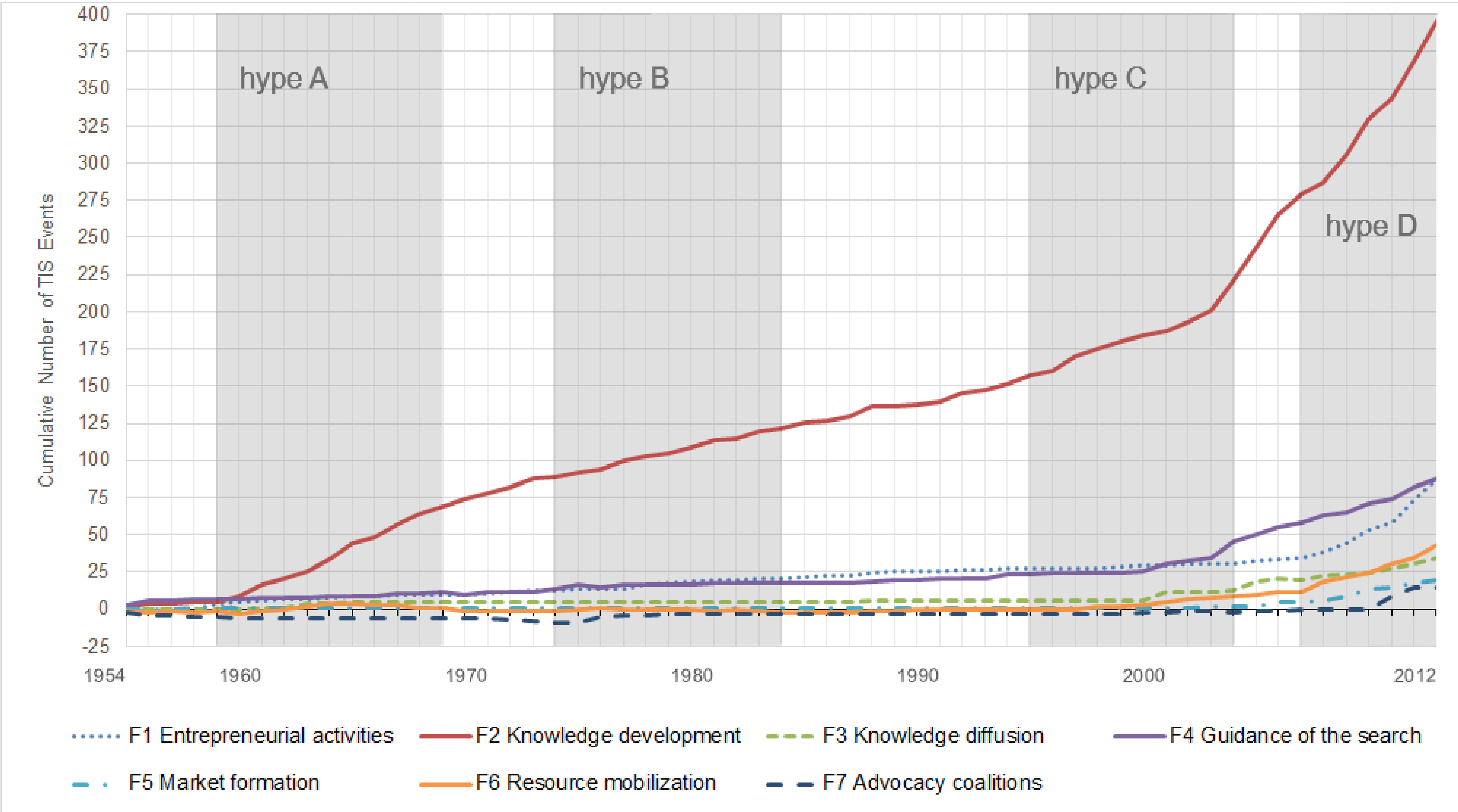
source: Macrotrends (2012) – inflation adjusted using the headline Consumer Price Index (with log y scale)

Figure 10: Global Oil Prices (West Texas Intermediate – WTI/NYMEX) – 1940s-2012



source: data in Appendix C

Figure 11: Annual Totals of Functional Activity in the UK HFC TIS



source: data in Appendix D

Figure 12: Cumulative Totals of All Functional Activity in the UK HFC TIS

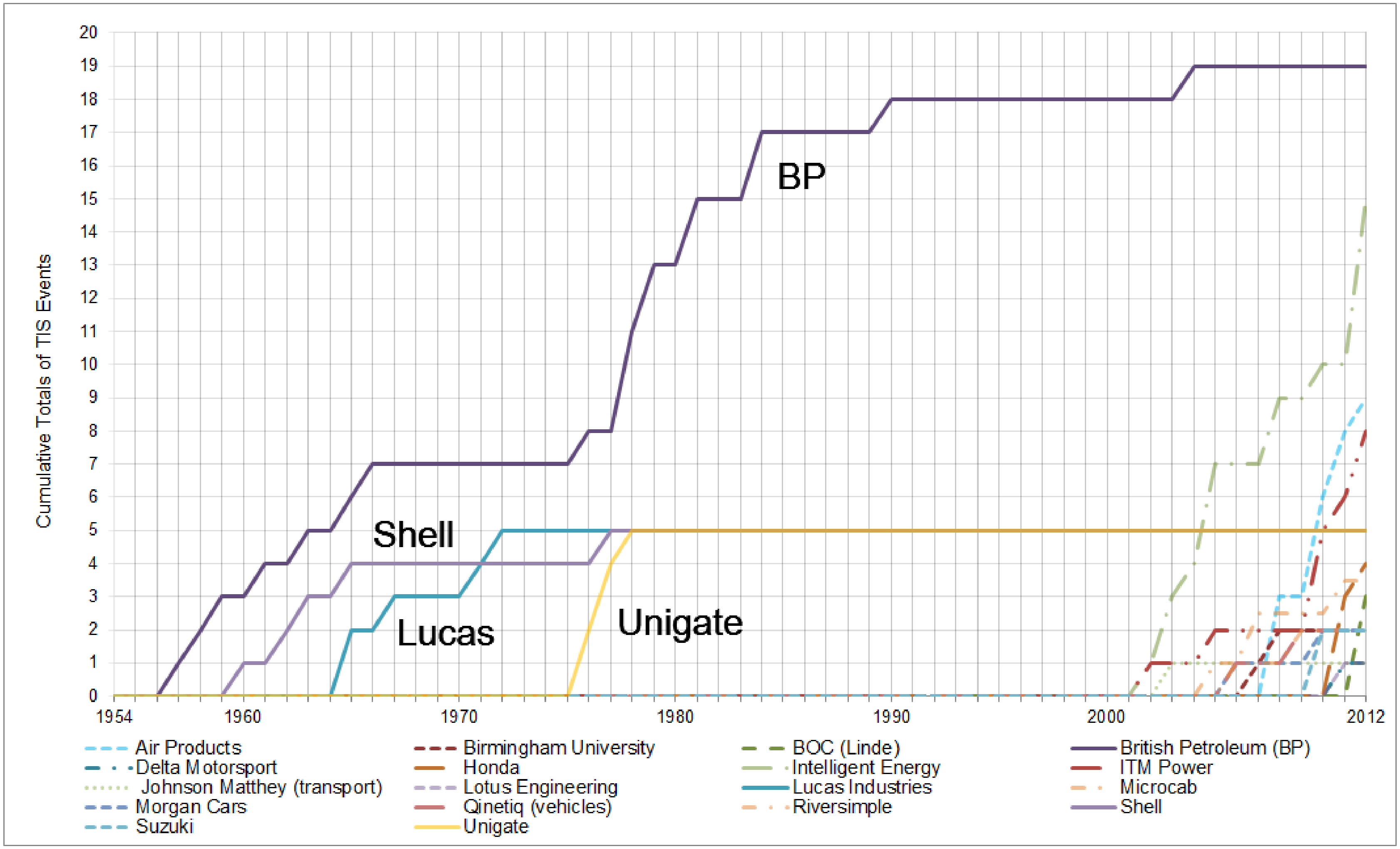
peaked at 11 events in 1963. During hype A, there was low-level knowledge diffusion (F3), market formation (F5) and resource mobilization (F6). However, from 1974 to 1999, the UK HFC TIS witnessed few events and almost no opportunities for cumulative causation. This was in large part because of a 'CoCoNuke' energy policy (conservation, coal and nuclear), the return of lower oil prices in the early 1980s and the weakness of the conventional automobility sector (cf. Suurs and Hekkert, 2012). During the early period of the HFC TIS' development (i.e. up to the late 1990s), a very weak *Science and Technology Push* (STP) *motor* may have briefly been at work (as per the theoretical picture in Figure 6), but no other motor could have been in play as feedback was very limited. This contrast in activity is evident in Figure 13 where the key automobility actors at work up to the end of the 1970s are different from those who were active from 2000 onwards. This is something not seen in other HFC-active countries like Germany and Japan. It suggests a potentially significant loss of tacit sectoral knowledge between hypes A and C.

4.1.2 Global Hype Cycle B and the 1973 Oil Crisis

Before the 1973 Oil Crisis, several UK-developed HFC prototypes showed promise. Different technological pathways included Shell's direct methanol fuel cell (DMFC) prototype vehicle described below. Pre-1973, energy policy advisors at the Energy Technology Support Unit at Harwell favoured funding HFC RD&D. Yet, when the UK's first formal energy policy appeared in 1974, energy R&D priorities were coal, conservation and nuclear: the CoCoNuke policy had limited funding for renewables (wave and wind) (Wilson, 2012). Hype B (1974-1983) witnessed rising *global* interest in HFCs due to energy security concerns, but the CoCoNuke policy meant the HFCs were locked out of funding and little growth or diffusion of knowledge occurred because of this institutional landscape. In 1973, the UK had a new supranational level of regulations from its accession to the European Common Market (Appendix E). This new tier of environmental governance began steering UK energy policy towards more sustainable goals with funding for HFC RD&D.

4.2 UK HFC Automobility Sub-sector

Innovative efforts in HFC automobility have been particularly responsive to external oil price fluctuations, e.g. Suez (1956), the 1973 and 1979 Oil Crises and the oil price rises around the Millennium (Figure 13 shows BP bucked this trend in the late 1970s). When details of the Bacon Cell were first published in 1954, multinational petrochemical and coal companies suggested to Bacon that hydrogen feedstocks for automobility prototypes should be based on reformed hydrocarbons, i.e. coal, oil and natural gas (McNicol, 1999). After Suez, HFC automobility



source: data in Appendix F

Figure 13: Cumulative Totals of Automobility Knowledge Development (F2) in the UK HFC TIS

technology assessments were undertaken by Shell and BP in the context of energy security. In Cambridge in 1959, Bacon trialled a 6kW Alkaline Fuel Cell (AFC) fork-lift truck which also helped fuel hype A. That same year, Shell's highly skilled electrochemists at Ellesmere Port began a dedicated research programme to build a prototype fuel cell electric vehicle (FCEV).

4.2.1 Shell's Fuel Cell Mobility Research

The technical challenges in creating an FCEV prototype were significant. Shell's researchers sought operating conditions close to ambient pressures and temperatures due to user safety. Existing gas electrodes performed poorly when operating with ambient air. Innovation centred on the diffusion of oxygen into the electrolyte and with the diffusion of nitrogen away from the catalyst's pores. In 1962, Shell invented a new platinum/ruthenium catalyst (McNicol, 1999). Direct methanol fuel cell (DMFC) stacks could then be developed as the power source. Using methanol as a fuel is safer than hydrogen as it is a liquid at ambient temperatures. A DMFC oxidizes liquid methanol fuel into carbon dioxide and water removing the need for a pressurised external hydrogen fuel supply. Smaller DMFCs were built ranging from a few watts up to several kilowatts (Cameron et al., 1987). Shell's composites functioned well with air. Fuel-cell electrodes with a large surface area became possible at low cost. Several stacks, including a 5kW unit, were built into a small DAF 44 passenger vehicle by 1968. Pure hydrogen came from a methanol–water mixture. This was purified via a palladium–silver diffuser. This self-contained vehicle unit then started in under fifteen minutes and could respond immediately to load changes.

4.2.2 Private Joint Venture - Shell / Lucas Industries

In the early 1960s, Shell initiated a private joint venture with the major vehicle components' manufacturer Lucas Industries based in Birmingham in the West Midlands. Throughout the partnership, socio-technical aspects of the DMFC technical pathway were contested between individual team members. By 1967, some of Shell's researchers considered DMFC engineering to be the "most likely contender" for a future FCEV design. However, for some the DAF44 prototype was the "wild card in the pack" due to its use of potentially hazardous hydrazine hydrate solution (McNicol, 1999, 7).

Shell's efforts were built on several electric vehicle (EV) technological advances in the global automobility sector. Most multinational vehicle manufacturers operating in the UK were developing various EV drive systems and battery types. Nevertheless, in this competitive RD&D

arena for EVs, Shell's HFC team thought methanol could easily be added into existing vehicle refuelling infrastructure. Non-HFC transport actors disagreed.

Ultimately, these Shell and Lucas failed to gain legitimacy for their FCEV technological pathway in the hostile post-1973 policy arena. Shell also struggled with unsuccessful trials of small stationary 500W DMFCs for leisure applications (caravanning and boating). A few years after the second global oil price shock in 1979, the price of oil returned to its post-1973 levels (Figure 10). Shell's FCEV R&D nevertheless stopped in 1982. Shell's management felt that while the institutional-level selection environment remained less favourable, the DMFC FCEV no longer satisfied commercial and performance expectations (McNicol, 1999).

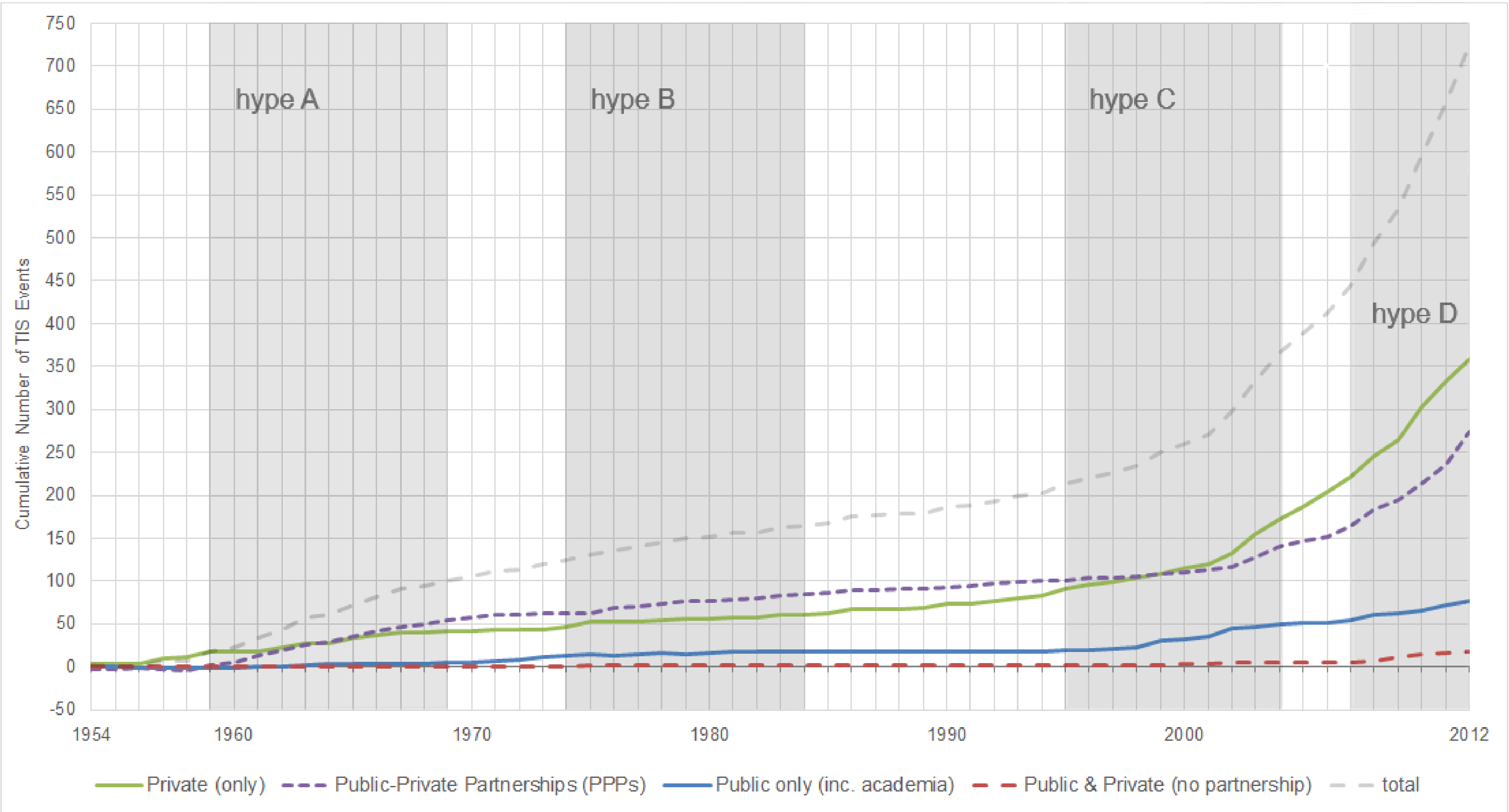
4.2.3 EV and FCEV Developments Halt

In the 1980s, UK FCEV and EV programmes lost state and private support as dominant designs failed to emerge (cf. Hekkert and den Hoed, 2004). National/regional competitive advantages in terms of such knowledge, both tacit and coded, were lost. The perceived global availability of oil and gas (chiefly from the North Sea) contributed to oil prices largely remaining relatively low around the globe well into the 1990s (Figure 10).

4.2.4 Global Hype Cycle C Begins (1995-2004)

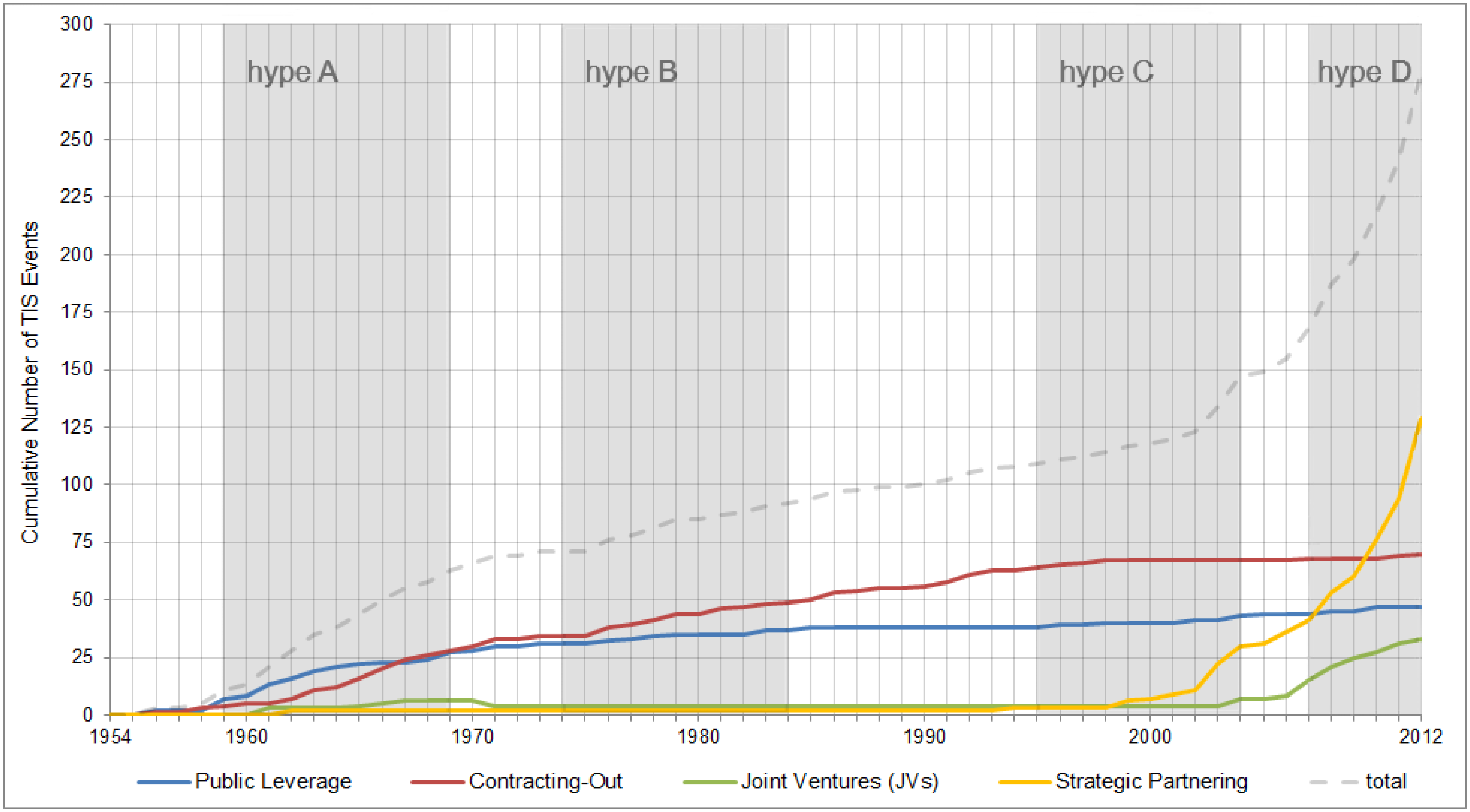
The 1980s to 1990s saw a long period of relatively little HFC activity in the UK TIS apart from submarine equipment manufacture for the Royal Navy. New private HFC JVs and PPPs then began appearing globally in the mid-1990s around the time of the Kyoto Protocol (1997) and in a period of rising oil prices (for the rise of UK PPPs see Figure 14 and for the rise of different PPP types, most notably 'strategic partnering', see Figure 15). In Europe, new HFC efforts built on existing Auto/Oil Programme collaboration. A period of global hydrogen hype began in the late 1990s. Shell and BP re-engaged with global motor industry actors raising expectations about refuelling hydrogen vehicles (McNicol, 1999, van den Hoed, 2005). Oil reforming was the preferred technological route of for hydrogen feedstocks. In 2000, Shell's CEO, Mark Moody-Stuart, backed on-board conversion of gasoline to hydrogen. This sent a strong signal to the marketplace about this particular HFC technological pathway.

In the UK, unlike Germany, Japan, South Korea and the US, no significant homegrown vehicle equipment-manufacturing partners existed. Only Japanese foreign direct investment brought significant new R&D funds (Whisler, 1999). Shell opted for a joint venture with Ballard in



source: data in Appendix G

Figure 14: Cumulative Totals of the Ownership of Innovative Activity in the UK HFC TIS



source: data in Appendix H

Figure 15: Cumulative Totals of the Types of Public-Private Partnerships in the UK HFC TIS

Vancouver, the leading HFC manufacturer in the world. In 2003, they opened a demonstration hydrogen filling station in Iceland (Park, 2011). UK HFC automobility activity slowly picked up amongst a handful of smaller vehicle manufacturers. One of these, ZeTek Power Plc, expanded quickly during the initial technological promises made during Hype C, only to go bust in 2001. The result was a sudden (but temporary) end for the AFC route to automobility (see below).

4.2.5 ZeTek Power Plc

In 1996, ZeTek Power Plc formed from the remains of leading Belgian AFC developer, Elenco, which was in receivership. Importing Elenco's AFC technology to the UK and to other countries where he planned to manufacture zero emission cars, ZeTek's British managing director, Nick Abson, was able to build up a new AFC vehicle division, Zevco Ltd - 'zero emissions vehicles company' – from 1998. In the mid-1990s, there was a surge in interest in another HFC technological pathway, proton-exchange membrane fuel cells (PEMFCs). This interest was thanks chiefly to the giant German automaker Daimler's commitment to PEMFCs. This activity went back to the early 1990s with international joint venture vehicle development work with Canadian pioneer fuel cell maker Ballard. In spite of Daimler's commitment to PEMFCs, Zevco's engineers felt AFCs were overlooked. Significant updates to AFC stack technology were produced. These resulted in a hybrid EV AFC powered by pure hydrogen. A lead-acid battery offered 5kW of power. Small demonstration fleets in the UK were run in Greater London and the South-East regions by the City of Westminster, Marks & Spencer and the Post Office.

4.2.6 Private Joint Venture - ZeTek Power Plc / London Taxi International

A prototype AFC-powered black taxi was produced by ZeTek with Coventry-based London Taxi International. ZeTek Power's system configuration was considered reliable and offered promising performance. Expectations rose and several technological promises about this AFC unit's performance were made. However, plans for commercial manufacturing of ZeTek's AFC cells - in highly automated factories in Germany and the US - were suddenly halted. The 9/11 World Trade Centre attack shut down the US banking system just as ZeTek was set to complete on funding from venture capitalists. The company went out of business for lack of liquidity. Rightly or wrongly, it was an outcome that left many stakeholders, including investors, critical of Abson and his management of the Gartner hype cycle where global expectations rose (1995-2001) before falling back (2001-4) (Fagan, 2001; Interviewee UKLOB1 - 2011).

The late 1990s and early 2000s witnessed an increasing number of state agencies becoming involved in supporting niche HFC activity via strategic PPPs, reflecting the need to share risks and help entrepreneurs avoid ZeTek's demise (Appendix I). These are described below in the context of place-specific HFC policies in England, Wales and Scotland (Appendices J, K and L respectively).

4.2.7 Strategic Planning PPPs - HFC Automobility Demonstrations

In the 2000s, fleet trials in major global cities picked up. London is a significant showcase for HFC demonstration fleets. For public and private operators, the high visibility for zero emission vehicles helping to cut emissions is attractive for legitimacy and investment. The UK public began experiencing HFC buses, taxis and scooters thanks to strategic partnering PPPs. Between 2003 and 2006, Greater London hosted the European CUTE and HYFLEET CUTE HFC bus demonstrator programmes. This well-funded activity was organised by a strategic partnering PPP involving DaimlerChrysler, BP, the Greater London Authority and the European Commission (Gonçalves et al., 2008). Since then, a hydrogen-powered demonstration bus service, the RV1, started operation via a strategic partnering PPP collaboration between the Greater London Authority, Transport for London, London Bus Services Ltd, Wrightbus, Ballard, ISE Corp and Air Products Ltd. UK-based HFC companies, ITM Power and Intelligent Energy, also ran vehicle trials in London for black cabs and scooters, respectively at this time.

4.2.8 Strategic Planning PPP - Outer Hebrides Council and Pure Energy Centre

HFC policies typically emerge where place-specific sustainable outcomes are sought. A council member involved in a significant island HFC demonstration in Na h-Eileanan Siar, the local council in the Outer Hebrides in north-west Scotland, said of the community:

> "They're very close to the consequences … of climate change and the consequences of continued fossil fuel use … The costs of energy … have always been higher here, so the prospect of lower cost energy is one that's very attractive … They're starting to see that hydrogen offers more … possibilities." (Interviewee SCO7, Na h-Eileanan Siar - 2011).

In the mid-2000s, the council went into a strategic partnering PPP with the Promoting Unst Renewable Energy (or PURE) Energy Centre, based in Shetland. Pure Energy runs the world's first community-owned renewable energy project using wind power and hydrogen storage.

Primary and secondary sources reveal significant internal policy debates within the council about HFCs' utility in achieving such desired policy goals (Hacking, 2017).

Pure Energy later advised the council about a phased demonstration project designed to overcome the high costs of imported fuel. The Hebridean project went on to examine a value chain of hydrogen technologies: biogas production, hydrogen storage, a hydrogen filling station, and hydrogen use in both stationary and transport applications.

4.2.9 Summary Picture of UK HFC TIS by 2012

Overall, by 2012, the UK hydrogen fuel cell (HFC) Technological Innovation System (TIS) involved a very broad range of actors operating at multiple levels from the regional to the supranational (Figure 16; see details of key state agencies in Appendix I). As suggested by Figure 5's theoretical approach to boundary relations, the UK HFC TIS can be thought of as linked to just one of several national systems of innovation (NSIs), e.g. Germany, Japan, South Korea and the US, and set in an evolving global TSIS which is subject to landscape-level social, economic and environmental events, many of which are linked to oil security.

Ultimately, however, the uneven geographical distribution of HFC research centres by 2012 (Figure 17) – where regional over- and under-representations of HFC research institutions have largely persisted throughout the study period - suggests a systems-oriented, neofunctional explanation of uneven development that aggregates results from case studies, such as those in the automobility sub-sector, may be missing key dimensions that would help with understanding the limits of actor agency, e.g. funding status and spatial location (cf. Coenen et al, 2012; Hacking, 2017).

4.3 Analysis – TSIS Coding

The TSIS analysis pursued here comes with some caution given the generally low tallies of functions in Appendices C and D as compared to a larger country like Germany (Hacking, 2017). The seemingly significant upswing in event tallies during hypes C and D, as compared to hype A, is dominated by three out of the seven functions by 2012: 1) Entrepreneurial activity (F1) with 14 events; 2) Knowledge development (F2) with 26 events; and 3) Resource mobilization (F6) with 9 events. These results mean that for the first motor in Hekkert and Suurs' (2012) evolutionary typology – the *STP motor* – it is highly likely that feedback is occurring between *all* the functions (Figure 18 shows 2012's STP result; note that event tallies for each function are marked with

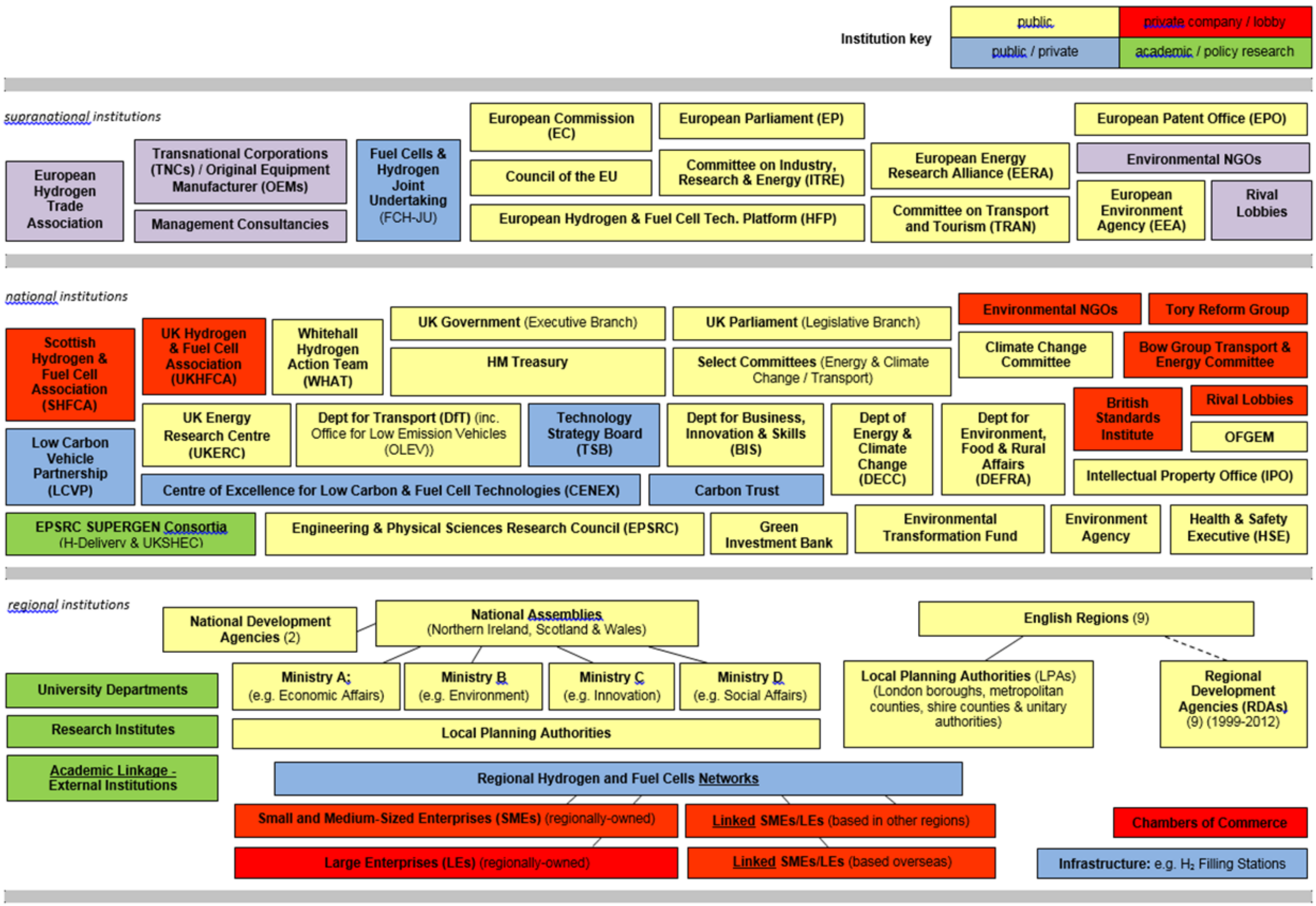


Figure 16: Multi-level Institutional Mapping of Actors Linked to HFC Actors in 2012

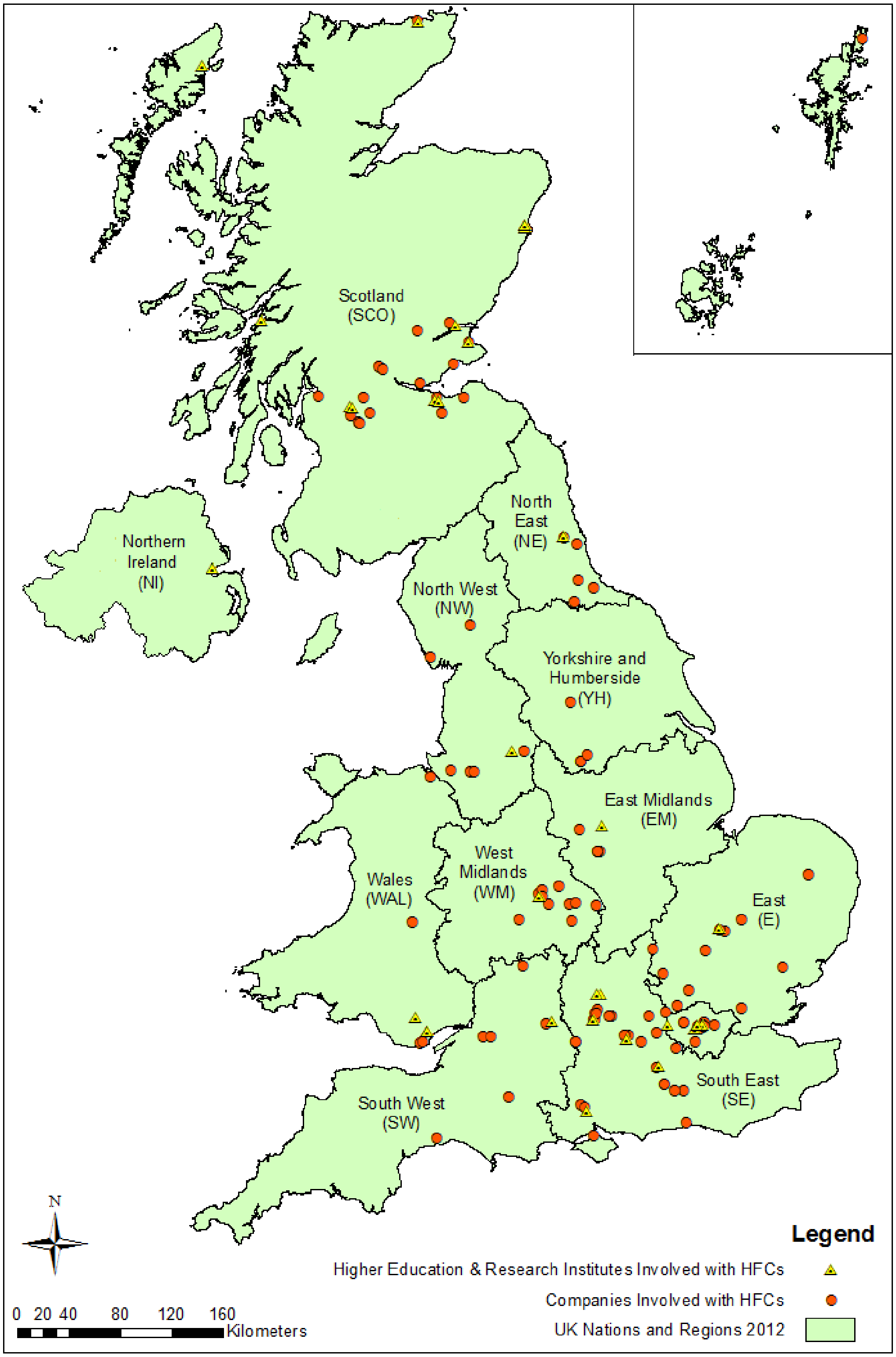


Figure 17: Uneven Geographical Distribution of HFC Actors in 2012

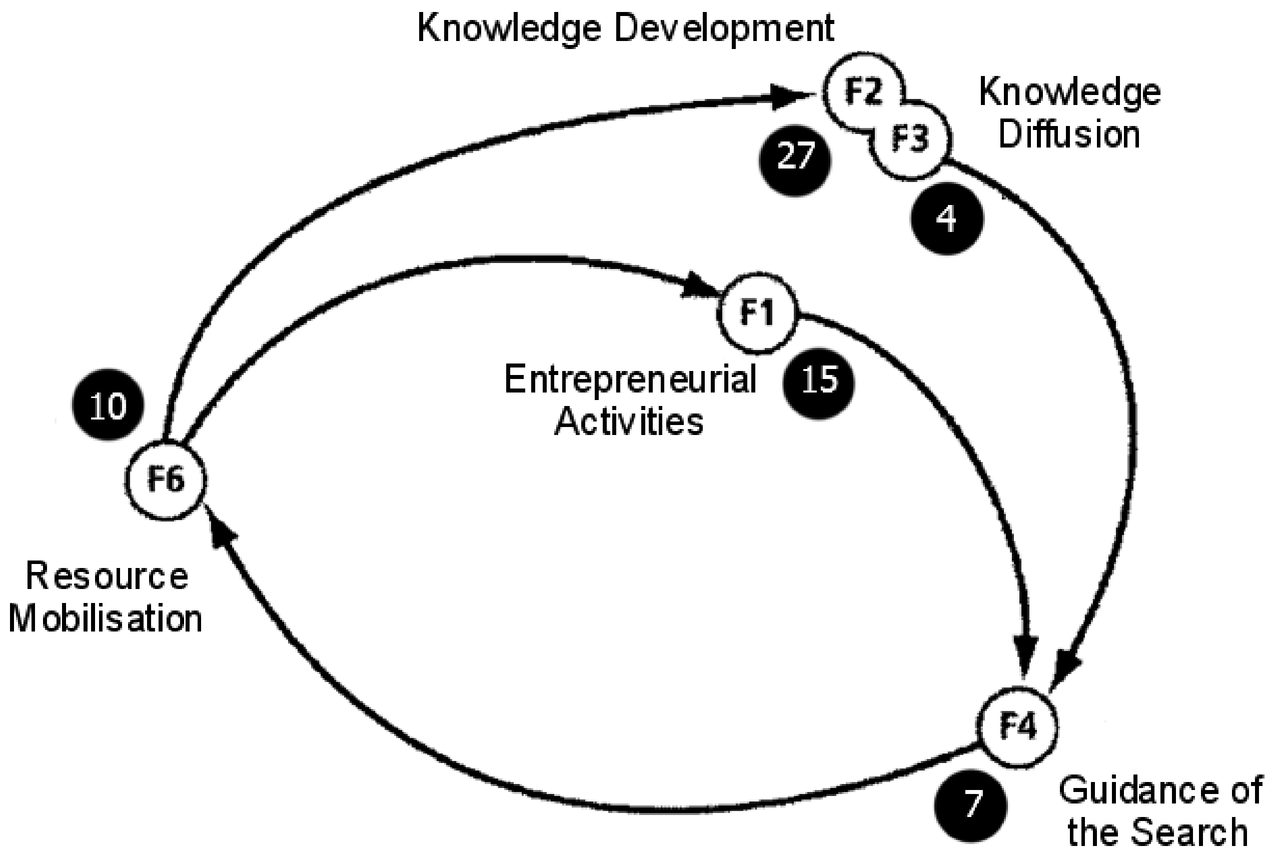


Figure 18: UK HFC TIS - Linked Functions with the Science & Technology Push (STP) Motor - 2012

white text in black circles). However, with the second configuration – the *Entrepreneurial motor* - the Advocacy Coalition (F7) function has no tallies in 2012 (Figure 19) suggesting a lack of positive feedback in part of this configuration. Similarly, the third motor in 2012 - the *System Building motor* – lacks any F7 tallies (Figure 20). However, in terms of the fourth motor for 2012 – the *Market motor* (Figure 21) – F7 is not involved and feedback between all functions exists.

Taken in the round, this lack of F7 tallies in 2012 appears less serious for the resilience of the UK HFC TIS than it first appears when quantitative and qualitative data sources are considered together. There is a general trend for all quantitative functional tallies to rise from the Millennium onwards (Figures 11 and 12). While the Advocacy Coalition function (F7), the most variable of the seven functions, scored 0 in both 2011 and 2012, it nonetheless tallied 9 and 6 in 2009 and 2010, respectively (Appendix C). Secondary source data on advocacy/lobbying activity for HFCs is inevitably hard to acquire, but in terms of primary source qualitative data, several HFC proponents/lobbyists at the UK Parliamentary level were interviewed for the Supergen XIV DoSH study. It was clear from that evidence that much behind-the-scenes advocacy activities – necessarily reported only on an off-the-record basis – was occurring in the early 2000s and 2010s and that the quantitative data alone, aggregated or otherwise, was only providing a partial picture of F7 activity.

To sum up the TSIS contribution, the aggregated EHA data suggests that early (and relatively brief) innovative HFC activity during hype A (1959-68) did not involve much feedback between functions HFC research was therefore not resilient and it largely disappeared in the face of institutional disfavour until the late 1990s. Later activity in hypes C (1995-2004) and D (2006-12) suggests greater potential for system feedback and hence improved resilience in the face of the next global downturn. To better understand why this has been the case, the additional coding described below provides further useful explanatory factors in the evolution of the UK HFC TIS.

4.4 Analysis - Additional Coding – Funding Type Indicators

Figure 14's cumulative graph shows how private funding and PPPs have been almost equally involved in supporting HFC innovative activity in the UK since the 1950s. By the time hype D occurs in the late 2000s, funding from private bodies was just outpacing that of PPPs. Figure 10 similarly shows that, of the four types of PPPs identified in the typology (Appendix A), partnerships were moving away from largely public leverage and contracting-out (both existed in the 1960s) to joint ventures (JVs) and strategic partnering with the latter picking up noticeably from 1998

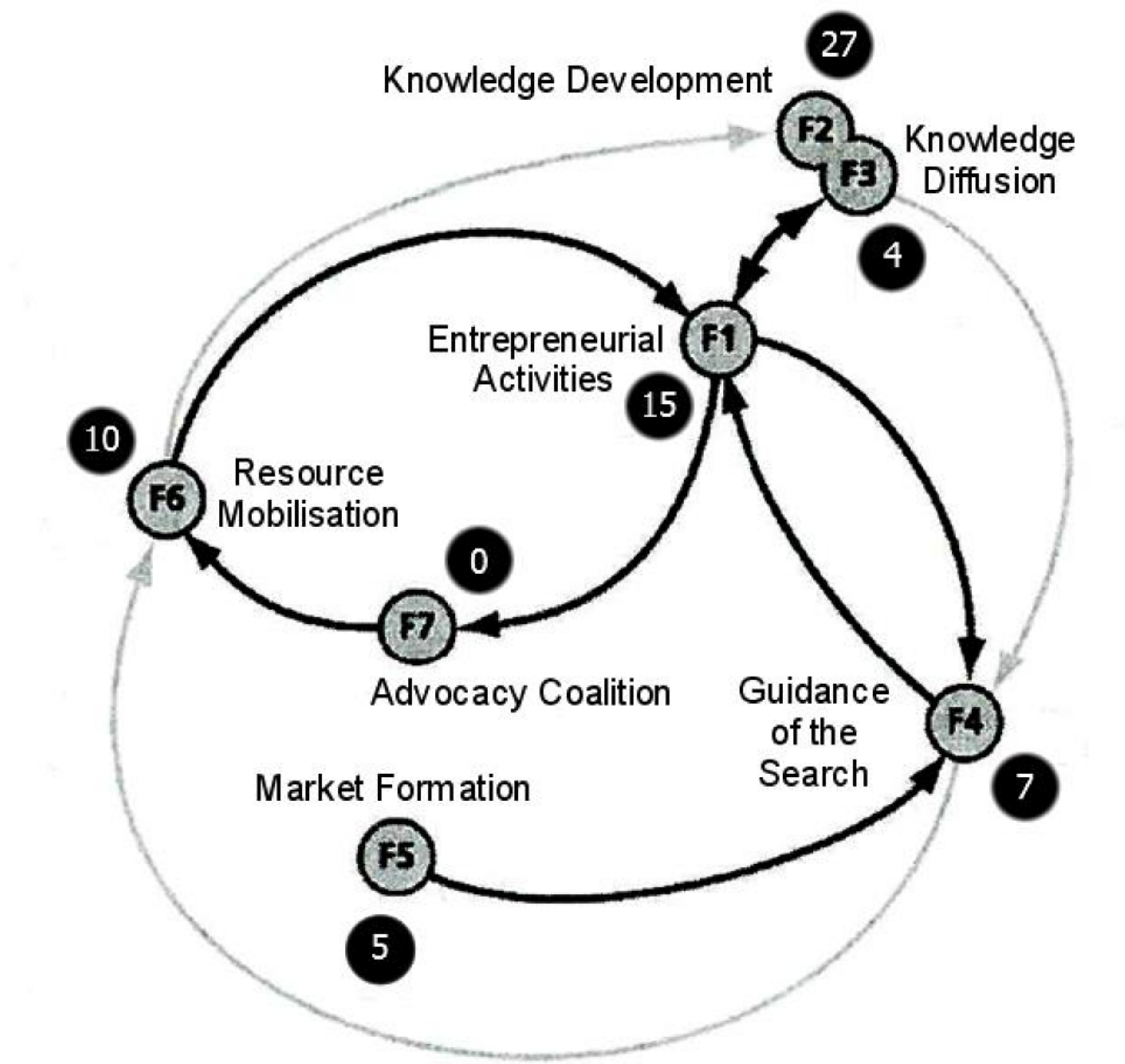


Figure 19: UK HFC TIS - Linked Functions with the Entrepreneurial Motor – 2012

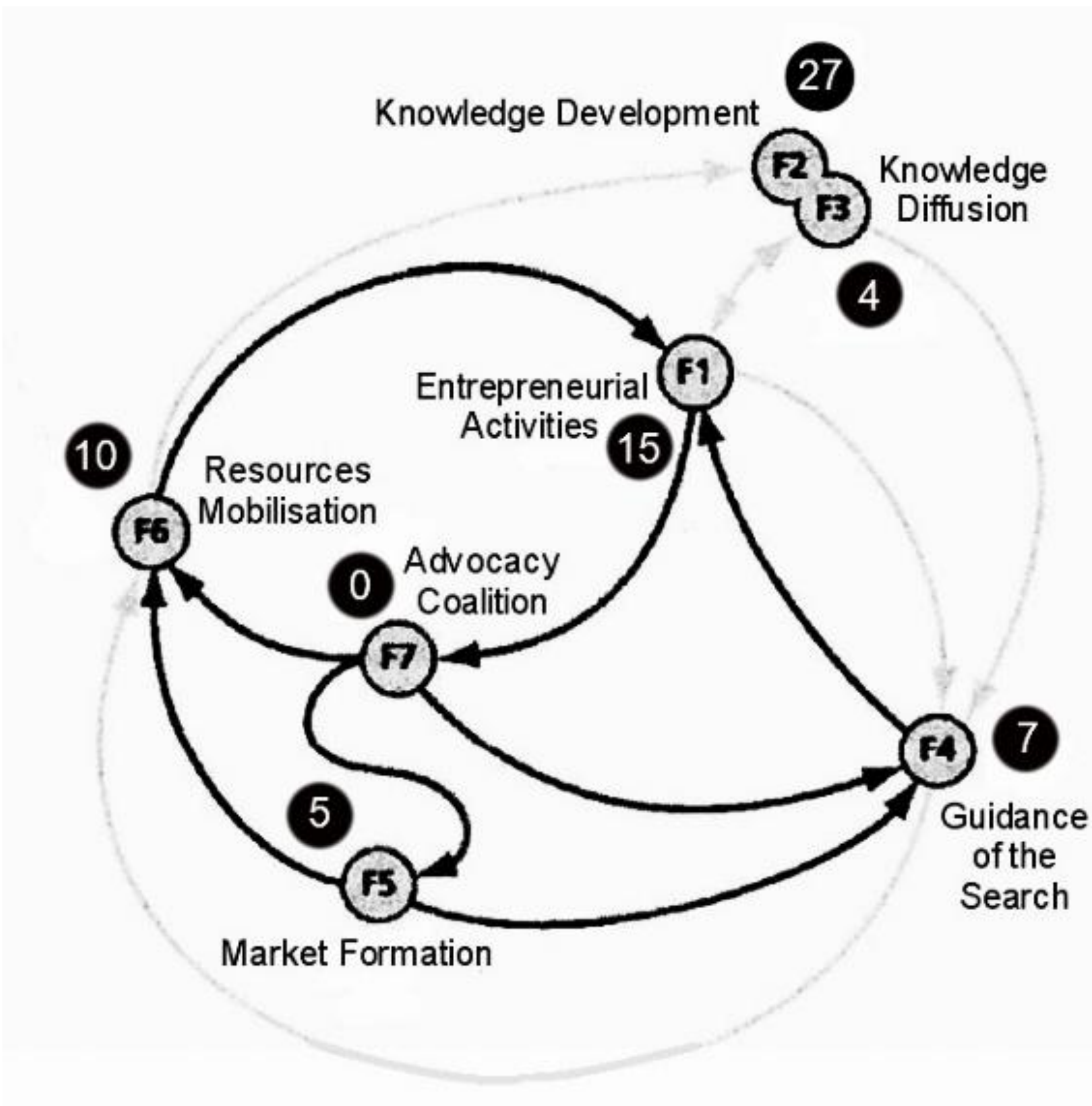


Figure 20: UK HFC TIS - Linked Functions with the System Building Motor - 2012

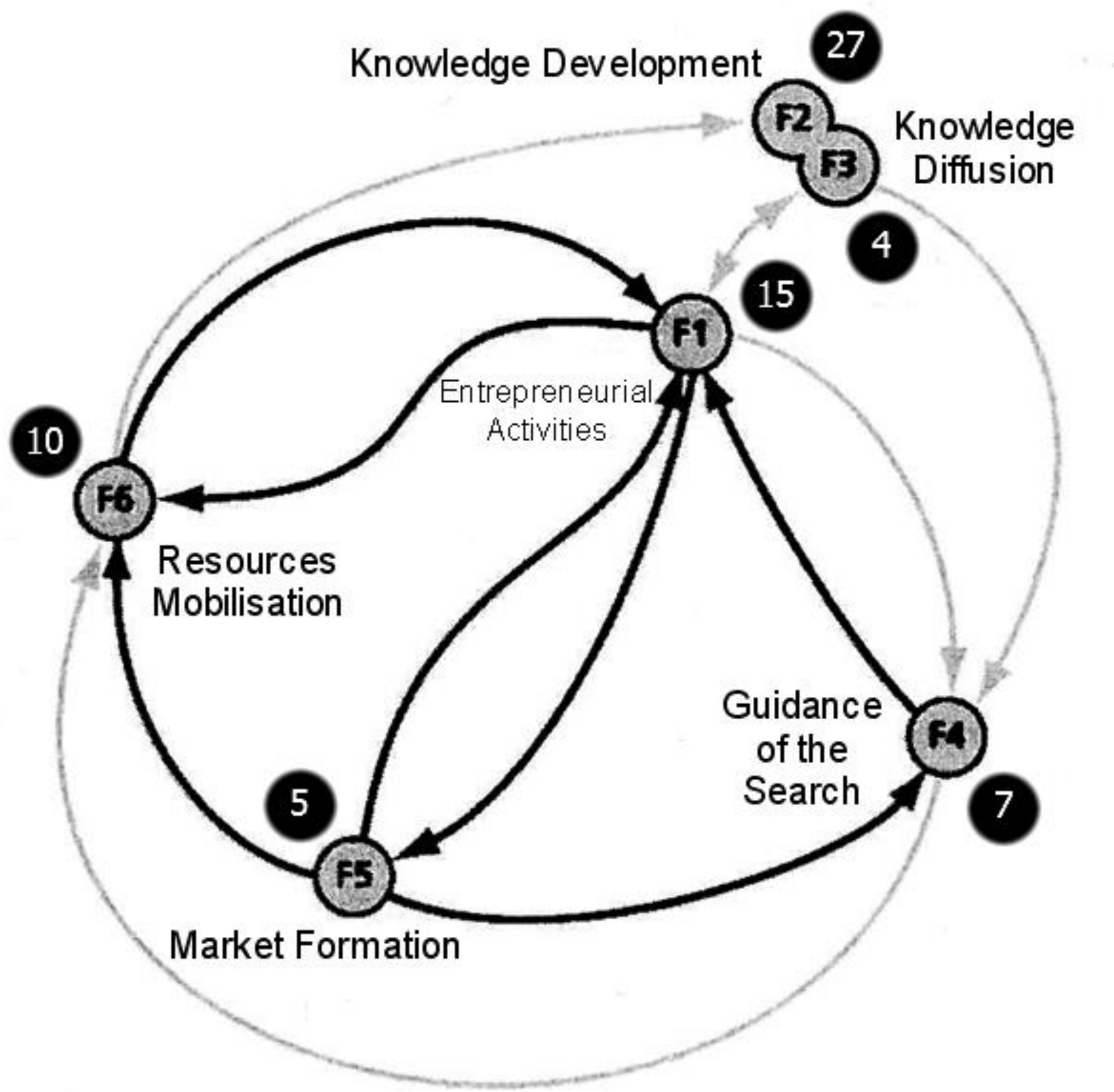


Figure 21: UK HFC TIS - Linked Functions with the Market Motor – 2012

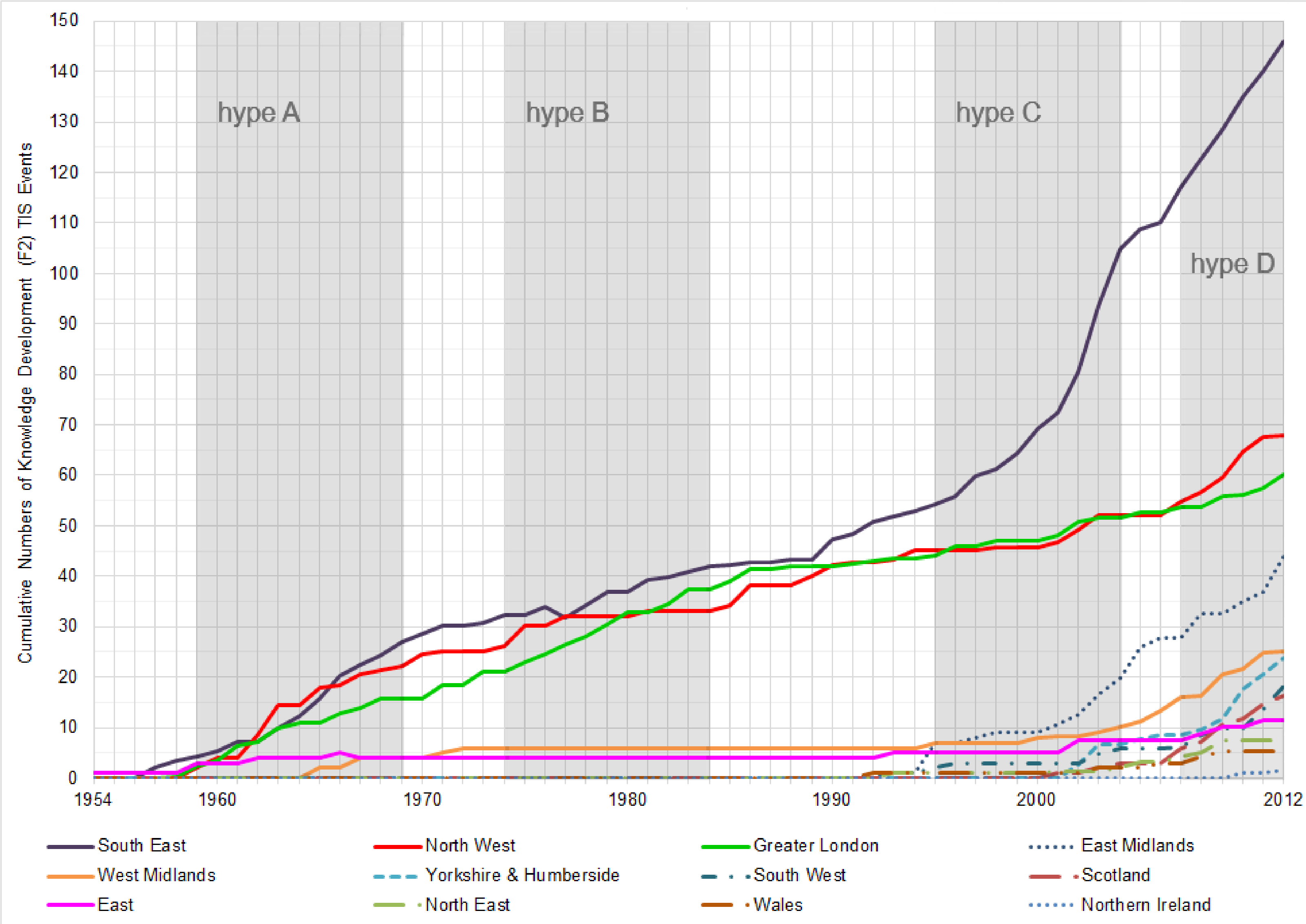
onwards.

4.5 Analysis - Additional Coding – Locational Indicators

In terms of geographical location, temporal and spatial data were merged to create a *spatio*-temporal events dataset. Analysis reveals an uneven picture of innovation and its regional diffusion across all sectors between 1954 and 2012 (Figures 22 and 23 cover Knowledge production, F2, and Entrepreneurial activity, F1, respectively). This situation appears to be linked in part to uneven structures of spatial governance, i.e. different levels of national and regional devolution. Figure 22 shows that, from the 1950s, HFC actors were operating chiefly in the South East, the East, Greater London and the North West regions. Specific sites had long-standing access to academic/industrial research centres and/or a workforce with very specific engineering and research skills. New entrant regions emerged during Hype C (e.g. in the East and West Midlands, Yorkshire and Humberside, and Scotland), but grew more slowly than the leading established region, the South East. Outside of steady growth in the South East, HFC innovation rates slowed in some other leading regions (e.g. the North West and Greater London). This suggests that, like other countries' capital city regions, the South East combines a strong potential for inward finance with global opportunities for exposure of HFC demonstration activities due to 'world city' status (this is something other UK cities cannot necessarily compete with). London's hosting of early fuel cell bus demonstrations was largely due to the *known* benefits accrued thanks to path dependence and the *perceived* potential benefits to PPP partners and investors of likely high public and private exposure at the global level (cf. Hodson et al., 2008).

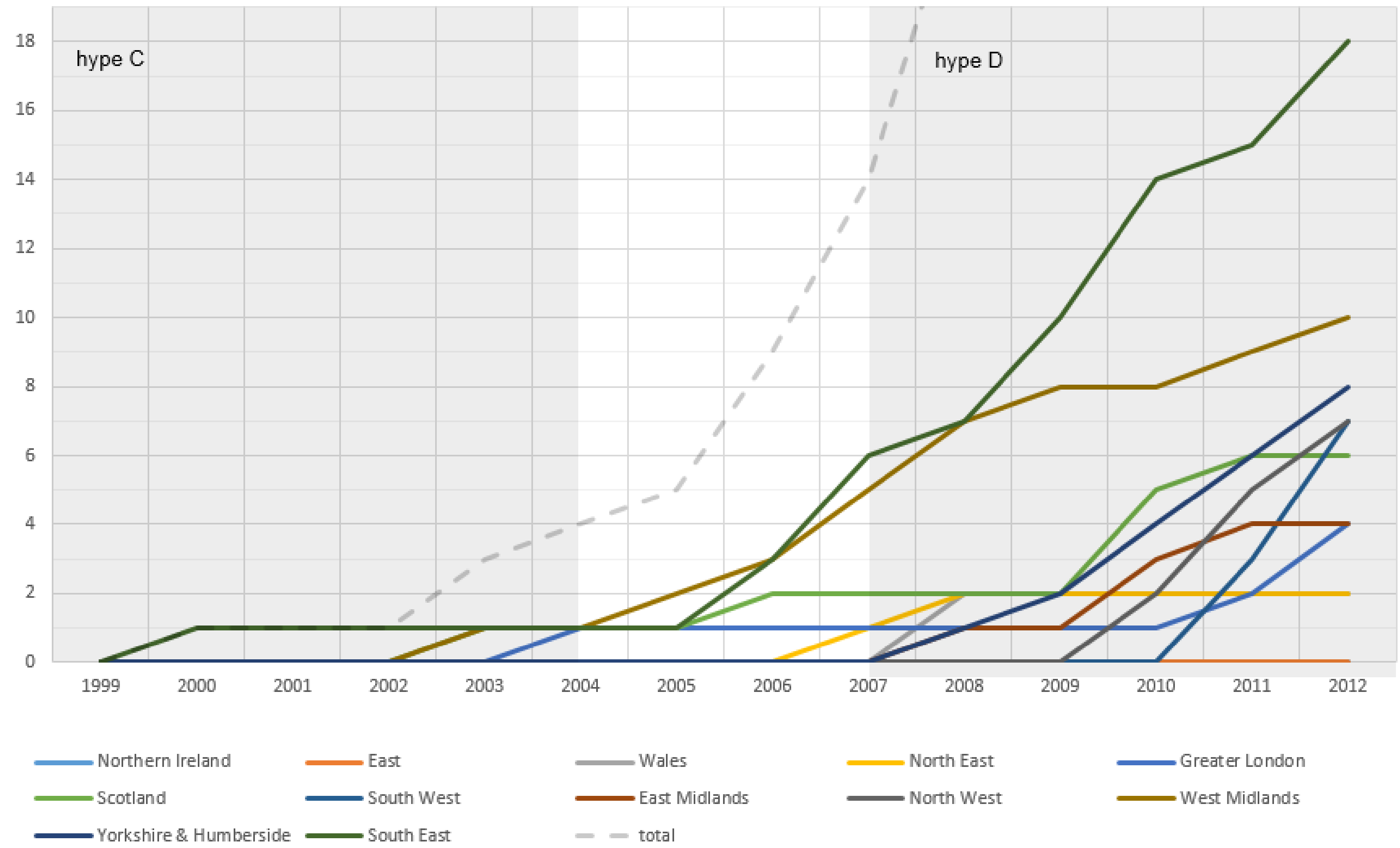
Regional growth differentials in entrepreneurial activity (F1) largely appear after 1999 (Figure 23). F1 and F2 at least weakly correlate with the regional use of strategic partnering PPPs (Hacking, 2017). This pattern of relative diffusion suggests that the large HFC actors active in the 1950s and 1960s were likely building on their historic competitive advantage (but the aggregation of data with the TSIS approach makes it harder to identify possible causes). Longitudinal evidence of regional shifts in knowledge development, where early innovation leads to later diffusion, is at least suggestive of path dependency based on historic competition for access to resources (Grabher, 1993). Further investigations at the micro level, beyond the scope of the TSIS approach, is needed to fully assess the validity of such an assertion.

Ultimately, spatial and temporal indicators suggest that cumulative causation is occurring unevenly in time *and* space (cf. Coenen et al, 2012). However, while the first new batch of regional



source: data in Appendix M

Figure 22: Regional Diffusion - Cumulative Totals of Knowledge Development (F2) in the UK HFC TIS



source: data in Appendix N

Figure 23: Cumulative Totals for Regional Diffusion of Entrepreneurial Activity (F1) in the UK HFC TIS

movers from 2001 (i.e. Wales and the North East) have valuable hydrogen infrastructure (chiefly pipelines) and the presence of automotive manufacturers and suppliers, they appear to underperform in relative terms up to 2012. They do not witness ‘hoped for’ HFC clusters (cf. Mans et al., 2008). Instead, the West and East Midlands regions fare better thanks to global and local academic-industry links. Such linkage was shown to be both geographical *and* relational – i.e. ‘global-local’ or ‘glocal’ – likely underpinning the institutional embeddedness of clustering activity within these regions (Heidenreich, 2012).

4.5 Analysis - HFC Automobility Sub-Sector

Early in the evolution of the HFC automobility sub-sector, HFC actors entered into corporate JVs (e.g. Shell and Lucas) and early PPPs (e.g. Bacon with ECL). HFC achieved limited activity in an institutional environment dominated by state RD&D funding for nuclear fission (Appendix O shows the early dominance of the UK’s nuclear RD&D spend) and prestige engineering projects like Concorde. Plans to diversify (and further diffuse) HFC technologies were typically halted by institutional resource cuts after major external events.

Firstly, with the institutional ownership of events, the additional coding revealed that the UK has deployed a number of HFC PPPs ranging from public leverage to strategic partnering. Early UK public leverage PPP efforts with Bacon’s stationary power applications consortium Energy Conversion Ltd failed in large part due to the civil service’s lack of coordination and poor commercial orientation. There was no agreed roadmap for HFC projects, no political champion and so private partners’ confidence fell away (Fishlock, 1971). Policy lock out between 1974 and 1998 revealed a long period of relatively weak networked agency and few prospects for innovation and diffusion. Resilience of HFC innovation at this stage was poor to non-existent.

In terms of different HFC technological pathways, a branching point in HFC mobility was reached in 2001 with the AFC mobility route stalling. This was largely due to ZeTek’s demise. Instead, the PEMFC designs of DaimlerChrysler, Ballard and Ford (all foreign-owned) advanced as the dominant HFC design (BMW’s hydrogen internal combustion engine running a close second) in R&D centres outside of the UK. Since 2001, HFC-specific policy learning amongst key actors has centred in large part on resilience, i.e. finding the best ways to maintain a profile while avoiding raising market expectations for a range of fuel cell technologies too far too soon (e.g. avoiding ZeTek’s demise) (McDowall, 2012, Hacking, 2017, Pollet et al., 2019).

In terms of policy, an interviewee from the UK Technology Strategy Board (TSB) argued that state-sponsored HFC RD&D via contracting-out PPPs - followed by state-led procurement – could be a successful route to stimulate the early growth of HFC applications in the UK:

> "We're really bad at [state procurement] ... [With] a lot of these technologies, it would be a Government that's going to take it up first, or [a] local authority … and then businesses are second and ... then you create the market." (Interviewee UKFIN4 – 2011)

In this context, state RD&D support in niches followed by targeted procurement appears to have been a useful way forward in this sector, but marketization efforts have been disappointing. However, HFC and other innovative vehicle manufacturing innovative activity in the UK largely takes place outside Greater London and the South East regions, as the Technology Strategy Board (TSB) interviewee indicated:

> "We've got Honda, we've got Nissan ... and ... the Nissan investment in the LEAF and [this] has shown that we can demonstrate ... the UK's the place to make these things ... We're still a large part of the [global] automotive supply chain. We make a huge number of engines ... Why not make all the fuel cells? We should be focusing on the high value end ... We've got a lot of expertise, design, consultancy, with integrating these technologies. [Get] the research happening here." (Interviewee UKFIN4, TSB – 2011)

One of the Carbon Trust interviewees suggested that, in 2011/2, the greatest technical challenges were reducing the cost of installing refuelling infrastructure and keeping the vehicle unit costs down:

> "The feedback that we're getting from major global OEMs is that the technology that they're putting in these cars ... is still too expensive … That's fine … That's the way it happened … when Toyota marketed the Prius … [But] without [unit cost reductions] their products ... will remain a niche. So [we want to] de-risk the technology to a point where it can be picked up by industrial end users, … build on ... the strengths of the UK research base, and … deliver quite significant carbon savings." (Interviewee UKFIN1, Carbon Trust – 2011)

One factor that cannot be ignored in the co-evolution of the UK HFC TIS was raised by an interviewee from Friends of the Earth who felt the oil industry might support future HFCs, but this kind of support could lead to a relaxation of the environmental governance of polluting vehicles/fuels *in the present*:

> "[The OEMs have] already got a strong voice within Government ... If they're saying we need to move forward in this direction then the Government will support it. [But] the fossil fuel industry has possibly had a vested interest in [hyping it] ... [They might think] 'We can carry on doing what we're doing because ... this magic technology is coming down the pipe'." (Interviewee LOB2, FoE – 2011)

However, in the case of Daimler, for example, there were genuinely high expectations in 2011 for the launch of HFC vehicles (Interviewee G-MNC4, 2011). With hundreds of millions of Euros spent via public and private R&D over decades, there was a continuing expectation that such investments could be recouped from sales and licensing of Daimler's HFC patents. No similar such UK-owned vehicle manufacturer existed in the UK in the 2000s. HFC actors in the UK transport sector appear likely to have to settle for being 'fast followers' with little influence over the direction of particular HFC technological pathways and investing in the HFC technologies of other nations when the cost, timing and availability are right (Williamson, 2010).

In summary, by 2012, UK HFC automobility actors clearly accepted the EC's direction of travel in terms of environmental governance. Some happily and some grudgingly accepted the rationale that HFCs needed developing alongside EVs to meet climate targets (Dodds and Ekins, 2014). These actors would also work with others on evolving standards, for example. However, the lack of central government commitment in the UK to a clear set of well-funded HFC policies was cited by most interviewees as the leading barrier to change.

5.0 Conclusions

This study provides new analysis of 60 years of hydrogen fuel cell (HFC) innovation in the UK. It was undertaken in the context of emerging critiques of the TSIS approach to innovation (Coenen et al., 2012, Hacking, 2017). A prior analysis of empirical data from the UK hydrogen fuel cell (HFC) TIS, the Supergen Delivery of Sustainable Hydrogen (DoSH) study suggested that data on institutional ownership and the spatial location of events could be useful additions to the TSIS heuristic (Hacking and Eames, 2012). To test this proposed approach, TIS event data from secondary sources were coded according to the methodology of Hekkert et al (2007). Ownership and spatial indicator codes were added. From analysis of this revised data (including via Suurs and Hekkert, 2012), this study offers new conclusions in three areas which have distinct implications for HFC policy (cf. Bergek et al., 2010, Tanner, 2014, Tanner, 2016).

First, the Technology-specific Innovation Systems (TSIS) approach of Hekkert and colleagues helped to identify increasingly positive feedback between HFC TIS system functions over a 60-year time frame in the UK. By 2012, TSIS analysis of this case study shows the beginnings of positive innovation feedback in the HFC Technological Innovation System (TIS). Data on how and when HFC technologies co-evolved with their institutional environment suggests that, over time, HFC RD&D branches along certain pathways and not others depending typically upon landscape-level events., e.g. 'failures' occur with Shell's DMFC FCEV and ZeTek's AFC prototypes. For TSIS proponents, these trajectories are largely determined by the structural and functional barriers and enablers that are encountered by actors (cf. Foxon et al., 2013, Bergek et al., 2008). HFC automobility barriers include: 1) the discontinuity created by UK's 1973 CoCoNuke energy policy, 2) the historic decline of the UK vehicle industry between the 1970s and 1990s, 3) the loss of tacit HFC and EV knowledge during 2), 4) the continuing lack of an integrated industrial strategy, 5) the lack of a political HFC champion, and 6) the lack of coordinated 'road maps' for change at least prior to 2012. Some resilience of knowledge development in the UK HFC TIS was in evidence in the 1960s and early 1970s, but it was eroded in the face of landscape events and institutional barriers (both linked to oil security). By the end of the 60-year time period studied, greater system resilience reappears despite a dip in activity roughly between 1982 and 1998. By 2012, the beginnings of transitional change with HFCs may have been occurring. Expectations for the future identified around the Millennium and later (Bockris, 2002, Eliasson and Bossel, 2002, McDowall and Eames, 2006) still remain high (e.g. Maggio et al., 2019), although events since 2012 indicate another dip in the Gartner hype cycle has occurred (Staffell et al., 2019).

Second, the gathering of empirical evidence on the UK HFC TIS suggests the value of additional indicators to the TSIS analytical approach. New funding source indicators of innovative events helped with the analysis of innovation system resilience and policy over time. To better understand *why* events unfolded in the ways they did between the 1950s and 2012, new organisational indicators were added to the TSIS methodology. This coding revealed how much 'funding type' – whether public, private or public-private – matters to analyses of HFC innovation and diffusion (Figures 22 and 23). In this context, coordinated public-private support for getting HFC RD&D activity out of its niches and into the marketplace began with PPPs in the 1960s and proved very significant from the 1990s onwards. During the latter period, PPPs ran a close second to corporate-only activity, overwhelmingly involved strategic partnering, and was associated with the knowledge development and entrepreneurial activity functions of the TSIS approach. The rise of strategic partnering with HFCs, clearly shown in Figure 23, reflects increasingly neoliberal approaches to capital in the UK where relatively limited state support for HFC infrastructure is used to attract significant private funding (cf. Hall and Soskice, 2001). This approach, used in conjunction with EHA, also increases confidence levels in the TIS event narrative.

Third, spatial indicators show that location matters. This is whether in terms of the Varieties of Capitalism practiced between countries, between regions or in terms of the networked and knowledge-based behaviour between sites. Spatial dimensions were added to TIS event coding and UK HFC activity was shown to be distinctly unevenly distributed in space (Figures 17, 22 and 23). Early regional HFC comparative advantage arose in particular places with links to vehicle manufacture (the West Midlands), oil company R&D (the North West) and academic, corporate headquarters and financial institutions (the South-East). Where this activity persists over time, spatial coding suggests it does so via the positive feedback involved in path creation and path dependency (cf. Garud et al, 2010). Spatial analysis therefore indicates that place should matter to TSIS analysis as much as time does. This suggests a need to revise the so-called 'global technological opportunity sets' approach (Carlsson, 1997, Carlsson et al., 2002) of early technological system theorizing, where actors are assumed to have even access to HFC resources. HFC TIS resources are unevenly distributed and unevenly exploited. Such place-specific contextual information should strengthen not weaken TIS/TSIS notions of causality (cf. Coenen and Díaz López, 2010, Coenen et al., 2012, Binz et al., 2014). For HFC policymakers, this approach would imply that, where no HFC activity currently exists in a country, region or locality, it will likely be extremely difficult to get it started even where resources like pipelines already exist (Mans et al, 2008).

Overall, this case study suggests that introducing an organisational and spatial dimension to the TSIS analysis means that strategic PPPs (in combination with state-led procurement) offer HFC automobility actors the greatest potential levels of agency and resilience. This finding also suggests that clusters in a particular locality become a useful focus on the entrepreneurial culture at the project level of innovative activity (Fritsch and Mueller, 2007). While overarching national and supranational policies are important, regional development strategies and policy measures need to be included to account for region-specific socio-economic development factors. Factors stimulating entrepreneurship, like regional tax and welfare arrangements and general economic development policies, appear important in the TIS narrative (cf. van Stel and Stunnenberg, 2004). The uneven distribution of resources (and the processes reinforcing uneven opportunities) suggest that UK policymakers should not simply label new HFC clusters (at whatever level of analysis) in the hope that they will thrive anywhere in space (cf. Mans et al., 2008). Hi-tech cluster policies must instead acknowledge historic regional resource endowments which may go back decades as well as support for underlying processes contributing to feedback with localised investments and knowledge growth. Policymakers can include market incentives to aid existing cluster cooperation, but this appears to be best linked to a coordinated green industrial strategy involving HFC innovation and diffusion, such as in Germany, Japan and South Korea, where governance actors can still draw on a wide range of policy levers (cf. Rodrik, 2013).

Finally, we suggest that future research should examine more HFC case study evidence for ownership and locational effects in national innovation programmes. In such cases, locality is not the result of general structural processes, but can instead be theorised as the outcome of relational networked associations in actor-space (Coenen et al, 2012). This would be redolent of a realist approach - methodological situationism – where social systems are created in local areas, and actor behaviour is shaped by responses to immediate situations (Murdoch and Marsden, 1995).

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Appendix A: Typology of HFC Public-Private Partnerships (PPPs) in the UK

	Public Leverage	Contracting-Out	Joint Ventures	Strategic Partnering
Purpose from State Perspective	i) Create conditions attractive to private sector investment. ii) Foster sectoral development in specific locations.	i) Achieve cost reductions, efficiency gains and quality improvements in public services. ii) Reduce the workforce management responsibilities of public managers.	i) Deliver projects where government has commonality of interest with business or not-for-profits. ii) Enable government to gain access to private capital off the public balance sheet. iii) Transfer risk to the private sector.	i) Enable government to gain significant cost and business process gains over the medium to long term. ii) Integrate business and not-for-profit actors into the public policy process.
Mechanism	Government prepares land for industrial development, provides tax breaks, and offers subsidies, e.g. capacity payments for electricity generation.	Provision of public service under contract by business, not-for-profit or any other agency, often utilising competitive tendering against the existing public provider.	Contract between government and private partners covering relative financial contributions to RD&D, design, capital works and subsequent costs.	Long-term and open-ended relationship between public and private actors based on trust and mutuality rather than formal contract.
Partner Relationships	Government seeks to attract business partners who will invest in RD&D generally but also in specific locations typically in need of economic regeneration.	Public.	i) Government commissions and specifies the project outcomes and commits to repaying costs. ii) Private partner finances RD&D, design, marketing, and/or builds, and/or manages, and/or operates facilities.	May include elements of contracting-out, franchising and/or joint venture.
Funding	Public	Public purchaser. Private or not-for-profit supplier.	Private, with government refunding costs over the long term.	Public, but may include private.
Timescale	Medium term. Open-ended.	Short-, medium- and long-term. Fixed period contracts.	Long term. Fixed-term contract.	Long-term. Open-ended, relational contract.

continued…/

Appendix A (continued): Typology of HFC Public-Private Partnerships (PPPs) in the UK

	Public Leverage	Contracting-Out	Joint Ventures	Strategic Partnering
UK Examples	In 2009 and 2010, the Department for Business, Innovation and Skills and the Department of Energy and Climate Change designated the North East, West Midlands and South Wales regions as Low Carbon Economic Areas. Financial support for R&D into low carbon vehicles was offered.	From 1959 to the present, the Admiralty (later, the Ministry of Defence) has had a long-term contract with CJB Developments Ltd. (and its successors) to provide electrolysers. This HFC technology has provided fresh water, oxygen and a source of electricity on board all of the UK's nuclear submarine fleet since 1962.	Energy Conversion Ltd. (ECL) was formed in Sunbury-on-Thames in 1961 by the non-departmental government body, the National Research Development Corporation (NRDC). This joint venture consisted of BP, British Ropes, GKN and the NRDC. BP saw the new HFC 'engine' as another outlet for oil, GKN for its electrochemical prowess, and British Ropes simply wanted to diversify.	In 2002, the Greater London Authority launched the London Hydrogen Partnership (LHP). The LHP strategically aligns public and private actors, legitimises HFCs, facilitates knowledge transfer and de-risks investment with the overall aim of establish a regional hydrogen economy. The long-term aspiration is to contribute to carbon reduction targets and boost the regional economy.

based on: Skelcher (2005)

Appendix B: National-level Legislation Influencing the HFC Selection Environment

Act / Policy Instrument	Aim	Impact Summary on HFC TIS
UK Atomic Energy Authority Act (HMG, 1954)	Create a single authority responsible for the UK's entire civil and military nuclear program.	This Act created a potential source of hydrogen linked to long-term prospects for a hydrogen economy. But, until the 1980s, significant financial resources, which could have been spent more widely on other energy RD&D, went into nuclear fission and fusion.
Clean Air Act (HMG, 1956)	Encourage industrial consumers of coal to re-evaluate their fuel choices.	The Act raised the prospect that governance of air pollution could be achieved. It indicated to actors that further regulations were likely. Innovators then stressed the low or no-emissions characteristics of certain applications. The Clean Air Act was updated in 1968 and 1993.
US-UK Mutual Defence Agreement (HMG, 1958)	Increase integration of the UK and US militaries particularly regarding nuclear technology transfer.	On the back of this agreement, a niche HFC application went into production: a cabin life support unit based on an AFC electrolyser. This innovation, based in part on US technology and in part on Bacon's work, was largely kept secret and the technology only diffused once (in the 1960s).
Continental Shelf Act (HMG, 1964)	Open up the North Sea to oil exploration.	As oil and gas deposits were identified and brought ashore between the 1960s and 1980s, the sense of urgency that emerged after each oil crisis amongst energy planners in Whitehall (in terms of security of supply) abated. This negatively impacted renewables and HFC RD&D.
Science and Technology Act (HMG, 1965)	Counter low levels of industrial productivity.	By turning the UK's academic research councils into autonomous civil research agencies with a new remit to engage industry, public-private funding of HFC RD&D took place in the 1960s.
Industrial Expansion Act (HMG, 1968)	Counter low levels of industrial productivity.	The activities of the Ministry of Technology ('Mintech') expanded further into industry. There were attempts to drop big defence projects in favour of small-scale civilian energy and transport projects (including HFCs). Mintech was broken up by the Conservative government in 1970.
Industrial Relations Act (HMG, 1971)	Reduce the power of the unions in the energy sector.	Subsequent strikes and power cuts left the country with a sense of its "overwhelming reliance on energy and … [its] vulnerability" (Wilson, 2012, 48). HFC advocates made much of HFCs' potentially positive contribution to energy security in the future.
European Communities Act (HMG, 1972)	Ensure harmonization between legislation passed in Brussels and the UK.	This Act boosted funding for HFC academic RD&D projects in the UK at a time when the post-1973 energy policy did not prioritise HFCs. The Act meant that the UK HFC TIS now had two levels of state governance which could drive technological change.

Energy Conservation (CPRS, 1974b) / *Energy 1974, And After* (CPRS, 1974a)	Set priorities for energy policy: coal, conservation and nuclear energy (termed 'CoCoNuke').	HFC RD&D was side-lined from 1974 to 1995 thanks to these reports. The CoCoNuke approach did favour wind and wave power, but HFC researchers were 'locked out' until Period 2.
Industry Act (HMG, 1975a)	Encourage hi-tech industrial activity with longer-term state financing.	The HFC transport sector benefitted from improved financing up to around 1981. However, the decline in the UK car industry in the 1980s meant alternative drivetrain RD&D largely stopped.
Scottish / Welsh Development Agency Acts (HMG, 1975b, HMG, 1975c)	Encourage regional industrial activity with longer-term state financing.	These Acts enabled PPP efforts in Period 2 with a third level of governance and funding in these nations. Regional PPP activity has included public leverage, JVs and strategic partnering.
Industries Development (N Ireland) Order (HMG, 1976)	Encourage regional industrial activity with longer-term state financing.	The Northern Ireland Development Agency (renamed Invest Northern Ireland in 2002), has been less active with HFCs (in Period 2) than its national partner agencies in Scotland and Wales.
Energy Act (HMG, 1983)	Let private generators trade electricity and access distribution networks.	The Act had the potential to lead to earlier support for, and development of HFC CHP units, but failed to do so in the context of the policy 'lock out' via the CoCoNuke approach.
Gas Act / Electricity Act (HMG, 1986) (HMG, 1989)	Deregulate the markets for gas and electricity supply.	Smaller companies entered the market. This shift helped HFC activity in stationary power in Period 2 because of partnering and competition between larger companies trialling CHP units.
Non-Fossil Fuel Energy Obligation (NFFO) (DTI, 1990)	Subsidize the nuclear sector.	This instrument forced electricity distributors to buy low carbon energy which, in an unintended way, boosted RD&D activity in the renewable sector (creating interest in hydrogen storage).
Environmental Protection Act (HMG, 1990)	Produce a national air quality strategy.	The Act encouraged a wide range of public and private actors to consider ways of complying with regulations via innovation.
Environment Act (HMG, 1995)	Produce national air quality & waste treatment strategies.	Further refined the governance of air pollution from a wide range of sources which has been a leading driver of HFC innovation in transport and stationary power.
Regional Development Agencies Act (HMG, 1998b)	Further economic development and regeneration; Promote business efficiency and competitiveness; Promote employment; Enhance the development and application of skills	The Act created nine RDAs in England to add to those already in Scotland, Wales and Northern Ireland. These pro-active non-departmental public bodies supported HFC RD&D efforts through the alignment of corporate and academic HFC actors via PPPs (public leverage, joint ventures and strategic partnering). Match funds and other organisational support came from Whitehall and Europe.

	relevant to employment and contribute to sustainable development.	
Scotland Act (HMG, 1998c) / *Government of Wales Act* (HMG, 1998a)	To give certain devolved powers to these nations.	The Scottish Parliament received devolved powers in energy giving it greater latitude than Wales in its plans for regeneration via renewable energy. The Welsh Assembly uses its duty under section 121 of the Government of Wales Act to promote sustainable development. Plans for a hydrogen economy in Wales were linked to the nation's commitment to 10%+ renewables by 2010 rising to 20% by 2020.
Waste Minimisation Act (HMG, 1998d)	Require local authorities to produce strategies for waste minimisation.	The effective governance of waste from a wide range of sources is a driver of HFC innovation. For example, markets have been expanding for the production and storage of renewable energy from waste (as well as hydrogen-from-waste).
National Cluster Policy (1998)	Encourage high-tech innovative actors to locate nearby and so benefit from knowledge spillovers.	The DTI pursued clustering in other sectors after examining the UK's spatially clustered biotechnology sector. Integrating HFC actors into high-tech clusters within the nations and regions has been a dominant policy approach to growth.
Pollution Prevention and Control Act (HMG, 1999)	Require local authorities to regulate smaller industry in terms of emissions and energy efficiency.	The effective governance of pollution and improved energy efficiency, asked for with this Act, are leading drivers of HFC innovation.
The Warm Homes & Energy Conservation Act (HMG, 2000)	Establish a target of ending fuel poverty 'as far as reasonably practicable' for all households within 15 years.	Lowering the unit cost of energy for the end user drives innovation and entrepreneurship in the HFC TIS.
Renewables Exemption from the Climate Change Levy (2001)	Exempt electricity from renewable sources from the Climate Change Levy.	Boosting market activity with renewables leads to innovation with HFCs: HFC renewable energy can be stored in hydrogen (as a vector).
Green Fuel Challenge (2001)	Achieve cleaner, greener road transport with alternative fuels.	HFC mobility began facing a strong challenge from biofuels after the major reductions in duty rates that came about with this instrument.
Sustainable Energy Technology Route Map for Hydrogen (2002)	Align the varied interests of the many UK HFC actors.	This route map, produced as part of the DTI's Foresight Vehicle Technology Roadmap, is said to have been effective in introducing HFC mobility actors into the UK HFC TIS.
Renewables Obligation (RO) (2002)	Subsidise RD&D into renewable energy.	Supporting the development of renewable sources of electricity struggling with carbon lock (so spurring hydrogen storage innovation), but, as with the NFFO, the RO's efficacy has been challenged.

CHP Exemption from the Climate Change Levy (2001)	Exempt indirect supplies of low carbon electricity for combined heat and power (CHP) schemes from the Climate Change Levy from 2003.	Creating a stronger market for CHP schemes encourages innovation via HFCs which offer unique, market-leading attributes.
Energy White Paper (DTI, 2003)	Focus on the environment, energy reliability, affordable energy, and competitive markets; a national 60% reduction in CO_2 production was required by 2050	Business opportunities were outlined for "cleaner, smarter energy" (DTI, 2003, 6) with HFCs' future use in zero-carbon buildings cited.
Energy Efficiency Implementation Plan (2004)	Improve the energy efficiency of residential accommodation in England.	This DEFRA roadmap encouraged greater energy efficiency via a range of renewable energy technologies. Greater demand for domestic energy efficiency accelerated innovation with HFCs in CHP units, in particular.
Climate Change and Sustainable Energy Act (2006)	Cut carbon emissions. Reduce fuel poverty via a micro-generation strategy.	Greater demand for domestic micro-generation has accelerated innovation with HFCs in CHP.
The Climate Change Act (2008)	Meet Kyoto and domestic CO_2 emissions targets; UK target of 80% reduction in six greenhouse gases by 2050 compared to the 1990 baseline.	HFC innovations in transport and stationary power involve zero emissions. If uptake of such applications is scaled up, then this has the potential to greatly improve air quality and human health.
The Planning Act (2008)	Speed up the process of approving new energy infrastructure projects inc. nuclear and waste facilities.	Potential to accelerate large-scale HFC infrastructure projects: e.g. pipelines, hydrogen fuelling stations, and stationary power plants.
Low Carbon Transition Plan (DECC, 2009)	Cut carbon emissions by 34% by 2020 (against 1990 benchmark).	Provided a broad governance framework for HFC actors. Key messages: i) radical rather than incremental technological change, ii) focus on reinvigorated transport sector, and iii) need decentralised stationary power schemes for communities.
Renewable Transport Fuel Obligation (RFA, 2009)	To require 3.25% of all fuel sold in UK to come from renewable source by 2010, and 5% by 2014.	Potential to help growth of hydrogen supplies in transport (the sustainability of some hydrogen feedstocks is contested). However, more readily available substitute fuels, like biofuels whose sustainability is also contested, were becoming more established.
Energy Act (2010)	Encourage carbon capture storage (CCS); propose new schemes for reducing fuel poverty; further regulate the gas and electricity markets via the Office of Gas and Electricity Markets.	CCS plants should produce hydrogen on a large-scale. Secondly, decentralised domestic energy schemes involving renewables, fuel cells and hydrogen storage can increase energy efficiency and security and reduce CO_2 and fuel bills. It is debatable whether investment in HFC RD&D is more likely with more deregulation in the UK energy market.

The Waste (England & Wales) Regulations (2011)	To prevent, reduce and manage waste.	This regulatory framework, transposed in line with EC legislation, has the potential to accelerate the construction of new energy-from-waste schemes (which can be linked both to decentralised hydrogen production and storage).
Ultra-low Emission Vehicle (ULEV) Grants (2011)	Support the early market for ultra-low emission vehicles (ULEVs) via a 25% grant towards the cost of new plug-in cars (to a maximum of £5,000).	This long-term framework of state support for the ULEV market gives greater investment certainty for HFC mobility actors developing FCEVs and FCVs (alongside approval under the UKH_2Mobility programme evaluation).
UKH_2Mobility programme evaluation (BIS, 2012)	Evaluate hydrogen as a fuel for ULEVs in the UK. Develop an action plan to match an anticipated roll-out to consumers in 2014/15 by German and Japanese OEMs.	UK HFC actors made their case for ULEV support via this review. State investments via PPPs were suggested to commercialise HFC mobility technologies. This includes RD&D and production facilities and refuelling infrastructure.
Energy Efficiency Strategy (DECC, 2012)	Increase energy efficiency and security and increase productivity through decarbonising the production of energy for heating.	This strategic framework was thought likely to encourage HFC stationary power actors to innovate and develop markets further for micro-CHP products, in particular.
The Renewable Transport Fuel Obligation (2012)	Encourage potential market growth from biofuels.	Biofuels came to the market ahead of planned HFC vehicle launches. HFC actors may benefit in the long-term if this support continues. However, there is a risk for HFC actors that biofuels become locked into the market making the future market entry of hydrogen more difficult.
Energy Bill (DECC, 2012a).	Close coal-fired power stations over two decades; continue financial incentives for reducing energy consumption; construct new nuclear power stations. Targets: produce 30% of electricity from renewables by 2020; cut GHG emissions by 50% on 1990 levels by 2025 and by 80% on 1990 levels by 2050.	These cuts in targets were thought likely to cause investors to drop out of funding clean technologies. A key recommendation was for buildings be virtually zero carbon by 2050. HFC technologies were said to be “a credible solution for many energy applications” (DECC, 2012, 51) with benefits in terms of intermittent supply from localised storage. The possible privatisation of the Government Pipelines and Storage System would be highly significant in terms of future large-scale hydrogen storage.

Appendix C: Annual Total Tallies of Functional Activity in the UK HFC TIS, 1954-2012

	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
F1 Entrepreneurial	0	0	0	4	1	1	1	0	1	1	0	1	0	0	0	1	1	1	0
F2 Knowledge dev.	2	0	1	0	4	7	4	5	8	11	4	9	7	5	5	4	4	6	1
F3 Knowledge diff.	0	0	0	0	0	1	0	3	0	1	0	0	0	0	0	0	0	0	0
F4 Guidance/search	3	0	1	0	0	1	0	0	1	0	0	2	0	1	-2	2	0	0	2
F5 Market formation	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6 Resources	-1	1	-1	1	-2	2	1	2	2	0	-1	0	-2	0	-2	0	0	0	0
F7 Advocacy build'g	-2	0	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1

	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
F1 Entrepreneurial	1	0	0	2	1	1	1	0	1	0	1	1	0	2	1	0	0	1	0
F2 Knowledge dev.	3	2	6	3	2	4	5	1	5	2	4	1	3	6	0	1	2	6	2
F3 Knowledge diff.	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
F4 Guidance/search	2	-1	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0
F5 Market formation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6 Resources	1	1	-1	0	0	0	-1	1	-1	-1	0	0	0	1	0	1	0	0	0
F7 Advocacy build'g	0	4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
F1 Entrepreneurial	1	0	0	0	0	1	1	0	1	0	0	2	1	1	4	6	9	5	15
F2 Knowledge dev.	4	6	3	10	5	5	4	3	6	8	20	23	21	14	8	19	24	14	25
F3 Knowledge diff.	0	0	0	0	0	0	0	6	0	0	1	5	2	-1	3	1	1	3	3
F4 Guidance/search	3	0	1	0	0	0	1	5	2	2	11	5	5	3	5	2	6	3	8
F5 Market formation	0	0	0	0	0	0	0	0	0	1	0	0	3	0	1	3	5	1	2
F6 Resources	0	0	0	0	2	0	1	2	2	1	1	1	2	0	6	3	3	6	4
F7 Advocacy build'g	0	0	0	0	0	0	1	0	1	0	-1	1	0	1	0	0	0	9	6

	2011	2012
F1 Entrepreneurial	15	15
F2 Knowledge dev.	27	27
F3 Knowledge diff.	4	4
F4 Guidance/search	6	7
F5 Market formation	2	5
F6 Resources	9	10
F7 Advocacy build'g	0	0

Appendix D: Cumulative Total Tallies of Functional Activity in the UK HFC TIS, 1954-2012

	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
F1 Entrepreneurial	0	0	0	4	5	6	7	7	8	9	9	10	10	10	10	11	12	13	13
F2 Knowledge dev.	2	2	3	3	7	14	18	23	31	42	46	55	62	67	72	76	80	86	87
F3 Knowledge diff.	0	0	0	0	0	1	1	4	4	5	5	5	5	5	5	5	5	5	5
F4 Guidance/search	3	3	4	4	4	5	5	5	6	6	6	8	8	9	7	9	9	9	11
F5 Market formation	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F6 Resources	-1	0	-1	0	-2	0	1	3	5	5	4	4	2	2	0	0	0	0	0
F7 Advocacy build'g	-2	-2	-3	-3	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-5	-6	-7

	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
F1 Entrepreneurial	14	14	14	16	17	18	19	19	20	20	21	22	22	24	25	25	25	26	26
F2 Knowledge dev.	90	92	98	101	103	107	112	113	118	120	124	125	128	134	134	135	137	143	145
F3 Knowledge diff.	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6
F4 Guidance/search	13	12	13	13	13	13	14	14	14	14	14	14	14	15	16	16	17	17	17
F5 Market formation	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F6 Resources	1	2	1	1	1	1	0	1	0	-1	-1	-1	-1	0	0	1	1	1	1
F7 Advocacy build'g	-7	-3	-2	-2	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
F1 Entrepreneurial	27	27	27	27	27	28	29	29	30	30	30	32	33	34	38	44	53	58	73
F2 Knowledge dev.	149	155	158	168	173	178	182	185	191	199	219	242	263	277	285	304	328	342	367
F3 Knowledge diff.	6	6	6	6	6	6	6	12	12	12	13	18	20	19	22	23	24	27	30
F4 Guidance/search	20	20	21	21	21	21	22	27	29	31	42	47	52	55	60	62	68	71	79
F5 Market formation	1	1	1	1	1	1	1	1	1	2	2	2	5	5	6	9	14	15	17
F6 Resources	1	1	1	1	3	3	4	6	8	9	10	11	13	13	19	22	25	31	35
F7 Advocacy build'g	-1	-1	-1	-1	-1	-1	0	0	1	1	0	1	1	2	2	2	2	11	17

	2011	2012
F1 Entrepreneurial	88	103
F2 Knowledge dev.	394	421
F3 Knowledge diff.	34	38
F4 Guidance/search	85	92
F5 Market formation	19	24
F6 Resources	44	54
F7 Advocacy build'g	17	17

Appendix E: Supranational-level Legislation Influencing the UK HFC Selection Environment

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
1st Environmental Action Programme (1973-1976)	The research agenda covered nuisance from pollutants, the causes of pollution, and approaches to setting criteria for environmental objectives.	National HFC researchers could henceforth legitimize their work on clean technologies in terms of further impending EEC environmental regulation. This was because the Treaty of Rome (1958) required the transposition of EEC instruments onto national statute books and for them to be subsequently enforced.
European Regional Development Fund (1975)	To overcome regional disparities in the European Economic Community (and later the EC).	The ERDF would later become an important source of funding for regenerating regions involving HFC RD&D as well as individual projects.
2nd Environmental Action Programme (1977-81)	To complete the internal market.	Suggestion that improvements in air quality could be achieved without strong state policy intervention. Onus placed on academia and industry to innovate via Europe-wide HFC RD&D funding programmes.
3rd Environmental Action Programme (1982-1987)	To harmonise environmental emissions standards to achieve a fair internal market.	HFCs' emissions benefits emphasized alongside economic benefits, e.g. employment gains from environmental policies, waste avoidance, efficient resource use and integrated environmental technologies.
The Brundtland Report (1987)	To produce more environmental policy integration within and between nations.	This UN-level report encouraged countries to coordinate sustainable thinking into social, economic and environmental policymaking.
4th Environmental Action Programme (1987-1992)	To reduce energy or material inputs and to close cycles to minimize waste.	Involved environmental impact of strategic economic sectors inc. energy and paved the way for governance via incentive-based instruments, e.g. taxes, subsidies or tradable emission permits seen in Period 3.
UN Framework Convention on Climate Change (UNCED (1992)	To produce international agreement on stabilizing greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system.	This broad driver of governmental change produced reassessments in the 1990s of the potential of clean technologies such as HFCs to help nations meet their international commitment to the UNFCCC.

5th Environmental Action Programme (1992-1999)	To orient policies towards ecological structural change via sustainable development (cf. Brundtland et al., 1987).	A sectoral approach favouring public transport, energy efficiency and waste prevention was pursued driving HFC RD&D. Market-oriented instruments and consensus building were encouraged.
Kyoto Protocol (UNFCCC, 1997)	Commit signatories to reduce greenhouse gas emissions	A broad driver of governmental change from the late 1990s and 2000s. The potential of clean technologies, including HFCs, to help nations meet international commitments was reassessed.
Directive on Electricity Production from Renewable Energy Sources (2001/77/EC)	Set indicative targets for renewable energy production in member states.	A rise in renewable energy use has helped make a case for sustainable hydrogen production and storage.
Energy Performance of Buildings Directive (2002/91/EC)	Help member states to comply with Kyoto in terms of hoped-for future cuts in domestic energy consumption.	Drove HFC innovation in decentralised stationary power units for residential and commercial premises via measures to reduce energy consumption and CO_2 emissions from boilers.
Electricity and Gas Market Directives (2003/54/EC	A liberalised, market stimulation approach aimed at removing barriers to cross-border trade and the disclosure of the origin of electricity and supplied to consumers.	Boosted potential consumer demand for a cleaner mix of electricity and gas supplies (with hydrogen as a storage option).
Energy Taxation Directive (2003/96/EC)	Progressively reduce tax on low carbon energy sources.	Hydrogen, with its potential for zero emission energy storage, were favoured by this legislation.
Directive on the Ecodesign of Energy-Using Products (2005/32/EC)	Improve products' energy efficiency over their entire life cycle.	HFC actors were favoured by this legislation because of the ever-increasing round-trip efficiency figures for a range of HFC product designs in Period 2.
Energy End-Use Efficiency & Energy Services Directive (2006/32/EC)	Set an indicative target for member states to improve energy efficiency by 1% on average every year up to the end of 2016.	(as above)
EU Waste Framework Directive (2008/98/EC)	For member states to deal with waste via the 'waste hierarchy' (actions ranked according to environmental impact).	This legislation includes reference to a range of waste technologies, including gasification and pyrolysis, which produce energy and hydrogen that can be stored

		and used with HFCs and electrolysers in a decentralised way.
Clean Air For Europe (CAFE) Directive (2008/50/EC)	Establish a long-term, integrated strategy to tackle air pollution. Protect against air pollution's effects on human health and the environment.	This legislation has the potential to accelerate existing moves being made by HFC actors in the transport and stationary power sectors to make innovations, diffuse knowledge and bring their products to market.
Renewable Energy Directive (EU-RED) (2009/28/EC)	Require 20% percent of energy consumed within the EU to be from low-carbon, renewable sources by 2020 via a National Renewable Energy Action Plan (all member states to submit one by 2010). Set a target of 10% renewable energy in transport by 2020 (the UK must achieve 15% of its energy consumption from renewable sources by 2020).	National renewable energy capacity rose across Europe in Period 2 helped make the case for sustainable hydrogen production and storage.
EU Regulation 443/2009	Establishes emissions performance of 120g CO_2/km as average emissions for the new car fleet.	Target can only be achieved by 2050 with more radical vehicle technologies, e.g. BEV, FCEV.
Fuel Quality Directive (FQD) (2009/30/EC)	Establish a low-carbon fuel standard (LCFS) involving reducing the transportation lifecycle greenhouse gas intensity by 6% by 2020.	Accelerate existing moves being made by HFC actors in the transport sector: innovate, diffuse knowledge and bring products to market.
Clean Vehicles Directive (2009/33/EC)	Introduce environmentally-friendly vehicles to the market. Ensure lifetime energy and environmental impacts linked to the operation of vehicles are taken into account.	Has the potential to accelerate existing moves by HFC actors in the transport sector: innovate, diffuse knowledge and bring products to market.
Energy Efficiency Directive (2012/27/EU)	Establish a binding set of measures covering the entire energy chain in Member States. Compliance is designed to help the EU meet its 20% energy efficiency target by 2020.	(as above)

Appendix F: HFC Knowledge Development (F2) TIS Events by Actor for Transport Sector, 1954-2012 (Part 1)

	event	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Air Products	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Birmingham University	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BOC (Linde)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
British Petroleum (BP)	annual	0	0	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	0	0	0
	cumulative	0	0	0	1	2	3	3	4	4	5	5	6	7	7	7	7	7	7	7	7
Delta Motorsport	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Honda	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intelligent Energy	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ITM Power	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Johnson Matthey	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(transport)	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lotus Engineering	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lucas Industries	annual	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	1	1	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	2	2	3	3	3	3	4	5	5
Microcab	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Morgan Cars	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Qinetiq (vehicles)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Riversimple	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shell	annual	0	0	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	1	1	2	3	3	4	4	4	4	4	4	4	4	4
Suzuki	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unigate	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
totals	annual	0	0	0	1	1	1	1	1	1	2	0	4	1	1	0	0	0	1	1	0
	cumulative	0	0	0	1	2	3	4	5	6	8	8	12	13	14	14	14	14	15	16	16

Appendix F: UK – HFC Knowledge Development (F2) by Actor for Transport Sector, 1954-2012 (Part 2)

	event	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Air Products	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Birmingham University	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BOC (Linde)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
British Petroleum (BP)	annual	0	0	1	0	3	2	0	2	0	0	2	0	0	0	0	0	1	0	0	0
	cumulative	7	7	8	8	11	13	13	15	15	15	17	17	17	17	17	17	18	18	18	18
Delta Motorsport	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Honda	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intelligent Energy	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ITM Power	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Johnson Matthey	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(transport)	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lotus Engineering	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lucas Industries	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Microcab	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Morgan Cars	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Qinetiq (vehicles)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Riversimple	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shell	annual	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Suzuki	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unigate	annual	0	0	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	2	4	5	5	5	5	5	5	5	5	5	0	0	2	4	5	5	5
totals	annual	0	0	3	3	4	2	0	2	0	0	2	0	0	0	0	0	1	0	0	0
	cumulative	16	16	19	22	26	28	28	30	30	30	32	32	32	32	32	32	33	33	33	33

Appendix F: UK – HFC Knowledge Development (F2) by Actor for Transport Sector, 1954-2012 (part 3)

	event	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Air Products	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	2	1
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	6	8	9
Birmingham University	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	2	2	2
BOC (Linde)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
British Petroleum (BP)	annual	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	cumulative	18	18	18	18	18	18	18	18	18	18	19	19	19	19	19	19	19	19	19
Delta Motorsport	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Honda	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4
Intelligent Energy	annual	0	0	0	0	0	0	0	0	1	2	1	3	0	0	2	0	1	0	5
	cumulative	0	0	0	0	0	0	0	0	1	3	4	7	7	7	9	9	10	10	15
ITM Power	annual	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	3	1	2
	cumulative	0	0	0	0	0	0	0	0	1	1	1	2	2	2	2	2	5	6	8
Johnson Matthey (transport)	annual	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
Lotus Engineering	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Lucas Industries	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Microcab	annual	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	1	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	3	3	4	4
Morgan Cars	annual	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2
Qinetiq (vehicles)	annual	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	2	2	2
Riversimple	annual	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	2	2	2
Shell	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Suzuki	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2
Unigate	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
totals	annual	0	0	0	0	0	0	0	0	2	3	2	5	3	3	6	2	10	9	12
	cumulative	33	33	33	33	33	33	33	33	35	38	40	45	48	50	56	58	68	77	89

Appendix G: TIS Events by Organisational Funding Type, 1954-2012

	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Public only (inc. academia)	1	-1	-1	0	0	0	0	2	0	1	1	0	0	1	0	1	0	2	1	3
Public & Private (no partnership)	4	0	0	6	1	6	1	0	4	6	0	5	4	3	0	1	1	1	1	0
Private (only)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
PPPs	-3	0	1	-1	-1	6	3	8	7	6	3	6	6	5	3	5	3	3	0	3
annual total	*2*	*-1*	*0*	*5*	*0*	*12*	*5*	*10*	*11*	*13*	*4*	*11*	*10*	*9*	*3*	*7*	*4*	*6*	*2*	*6*
cumulative total	*2*	*1*	*1*	*6*	*6*	*18*	*23*	*33*	*44*	*57*	*61*	*72*	*82*	*91*	*94*	*101*	*105*	*111*	*113*	*119*

	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Public only (inc. academia)	2	1	-1	2	1	-1	1	1	0	0	0	0	1	0	0	0	0	0	-1	1
Public & Private (no partnership)	3	5	1	0	1	2	0	2	0	2	1	1	5	0	0	1	6	0	3	3
Private (only)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PPPs	0	0	5	2	3	4	0	2	1	3	1	2	3	1	1	0	1	2	3	2
annual total	*5*	*7*	*5*	*4*	*5*	*5*	*1*	*5*	*1*	*5*	*2*	*3*	*9*	*1*	*1*	*1*	*7*	*2*	*5*	*6*
cumulative total	*124*	*131*	*136*	*140*	*145*	*150*	*151*	*156*	*157*	*162*	*164*	*167*	*176*	*177*	*178*	*179*	*186*	*188*	*193*	*199*

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Public only (inc. academia)	0	1	1	1	2	8	1	3	10	2	3	1	0	3	6	3	2	7	4
Public & Private (no partnership)	3	8	4	4	4	5	7	5	12	22	18	15	17	18	23	20	37	31	25
Private (only)	0	0	0	0	0	0	1	0	2	0	0	0	0	0	1	6	3	1	1
PPPs	1	1	2	1	2	3	1	3	3	11	13	6	6	12	19	11	19	23	38
annual total	*4*	*10*	*7*	*6*	*8*	*16*	*10*	*11*	*27*	*35*	*34*	*22*	*23*	*33*	*49*	*40*	*61*	*62*	*68*
cumulative total	*203*	*213*	*220*	*226*	*234*	*250*	*260*	*271*	*298*	*333*	*367*	*389*	*412*	*445*	*494*	*534*	*595*	*657*	*725*

Appendix H: HFC Public-Private Partnership (PPP) Types, 1954-2012

	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Public Leverage	0	0	2	0	0	5	1	5	3	3	2	1	1	0	1	3	1	2	0	1
Contracting-Out	0	0	1	0	2	1	1	0	2	4	1	4	4	4	2	2	2	3	0	1
Public JV	0	0	0	0	0	0	0	3	0	0	0	1	1	1	0	0	0	-2	0	0
Strategic Partnering	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
annual total	*0*	*0*	*3*	*0*	*2*	*6*	*2*	*8*	*7*	*7*	*3*	*6*	*6*	*5*	*3*	*5*	*3*	*3*	*0*	*2*
cumulative total	*0*	*0*	*3*	*3*	*5*	*11*	*13*	*21*	*28*	*35*	*38*	*44*	*50*	*55*	*58*	*63*	*66*	*69*	*69*	*71*

	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Public Leverage	0	0	1	1	1	1	0	0	0	2	0	1	0	0	0	0	0	0	0	0
Contracting-Out	0	0	4	1	2	3	0	2	1	1	1	1	3	1	1	0	1	2	3	2
Public JV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Strategic Partnering	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	*0*	*0*	*5*	*2*	*3*	*4*	*0*	*2*	*1*	*3*	*1*	*2*	*3*	*1*	*1*	*0*	*1*	*2*	*3*	*2*
cumulative total	*71*	*71*	*76*	*78*	*81*	*85*	*85*	*87*	*88*	*91*	*92*	*94*	*97*	*98*	*99*	*99*	*100*	*102*	*105*	*107*

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Public Leverage	0	0	1	0	1	0	0	0	1	0	2	1	0	0	1	0	2	0	0
Contracting-Out	0	1	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	1	1
Public JV	0	0	0	0	0	0	0	0	0	0	3	0	1	7	6	4	2	4	2
Strategic Partnering	1	0	0	0	0	3	1	2	2	11	8	1	5	5	12	7	16	18	35
annual total	*1*	*1*	*2*	*1*	*2*	*3*	*1*	*2*	*3*	*11*	*13*	*2*	*6*	*13*	*19*	*11*	*20*	*23*	*38*
cumulative total	*108*	*109*	*111*	*112*	*114*	*117*	*118*	*120*	*123*	*134*	*147*	*149*	*155*	*168*	*187*	*198*	*218*	*241*	*279*

Appendix G: Policy Instruments Affecting HFC Innovation and Diffusion in Selected English Regions

Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Strategy for Success (2001)	Adapt the existing industrial infrastructure, skills and economic processes to create new jobs and economic prosperity.	The RDA One North East used this regional economic policy to help align the different agendas of HFC stakeholders at the local, sub-regional, regional, national and supranational levels of activity in terms of the resource implications.
Tees Valley Action Plan (2001)	Create new jobs and economic prosperity in a specific district.	The RDA One North East used this regional industrial policy to help align the different agendas of HFC stakeholders at the local, sub-regional, regional, national and supranational levels of activity in terms of the resource implications.
Tees Valley Hydrogen Project (TVHP) (2001)	Encourage economic growth and raise educational attainment and skill levels.	A number of HFC demonstration projects in the Tees Valley in the early 2000s involved integration with buildings and monuments that symbolized the region's historical activity in petrochemicals, steel and coal.
Energy Innovation Zone (2001)	Break down socio-economic barriers and build upon local strengths to counteract continuing population and employment decline in the Outer Hebrides.	Public leverage of funding for activity including HFC demonstration work.
The London Hydrogen Partnership (LHP) (2002)	Strategically align public and private actors, legitimise HFCs, facilitate knowledge transfer and de-risk investment with the overall aim of establishing a regional hydrogen economy.	In 2002, the Greater London Authority (GLA) launched the LHP. The long-term aspiration was to contribute to carbon reduction targets and boost the regional economy.

Appendix I: UK State Agencies Affecting HFC Innovation and Diffusion

Body	Aim	Impact Summary on HFC TIS
Technology Strategy Board (TSB) (2004-)	Fund, support and connect innovative UK businesses. Accelerate sustainable growth.	Runs a Knowledge Transfer Network on HFCs. Funds certain demonstrations and competitions.
Energy Technologies Institute (ETI) (2007-)	Act as a conduit between academia, industry and the government to accelerate the development of low carbon technologies.	A PPP between global energy and engineering companies and the UK Government funded research into hydrogen fuels for CHP and CCGT applications. Tendered for hydrogen storage and flexible turbine systems research within its CCS programme.
Environmental Transformation Fund (ETF) (2008-2012)	Offer financial support for tackling climate change within the UK and developing countries.	ETF had the potential to reduce carbon emissions in the long term through the use of technologies including HFCs (ETF had an HFC Demonstration Programme).
Department of Energy and Climate Change (DECC) (2008-)	Ensure the UK has secure, clean, affordable energy supplies and promote international action to mitigate climate change.	In 2012, DECC began work with the Department for Transport (DfT) and the Department for Business Innovation and Skills (BIS) in a strategic partnering PPP with industry known as the UK H_2Mobility project.
Committee on Climate Change (CCC) (2008-)	Recommend five-year carbon budgets and make technology assessments towards 2050	The CCC is Independent of government Consisting of external energy and climate experts, the CCC's recommendations have included evaluations of the potential contribution of HFCs to low carbon innovation.
The Low Carbon Innovation Group (LCIG) (2009-)	Make technology-specific innovation needs assessments (TINAs).	A coordinating initiative between the Technology Strategy Board (TSB), the Carbon Trust and the ETI. Renamed 'Low Carbon Innovation Coordination Group' (LCICG) in 2011, this body had not yet produced a TINA for HFCs by the end of 2012.
The Infrastructure Planning Commission (IPC) (2009-)	Oversee nationally significant infrastructure projects (NSIPs) including new power stations.	The IPC has the potential to accelerate the delivery of major HFC infrastructure such as pipelines, power plants and large storage facilities.
Office of Low Emission Vehicles (OLEV) (2009-)	Support the early market for ultra-low emission vehicles (ULEV).	DfT-BIS cross-departmental unit focusing on i) energy storage, ii) electric machines, iii) light-weight vehicles, and iv) disruptive technologies. Electric vehicles are prioritized.
Whitehall Hydrogen Action Team (WHAT) (2009-)	Support coordinated HFC policy efforts and ensure delivery.	This HFC policy group is staffed by individuals from DECC and OLEV who helped to establish the UKH2Mobility policy review in 2012.

Appendix J: National/Regional Policy Instruments Affecting HFC Innovation and Diffusion in England

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Strategy for Success (2001)	Adapt the existing industrial infrastructure, skills and economic processes to create new jobs and economic prosperity.	The RDA One North East used this regional economic policy to help align the different agendas of HFC stakeholders at the local, sub-regional, regional, national and supranational levels of activity in terms of the resource implications.
Tees Valley Action Plan (2001)	Create new jobs and economic prosperity in a specific district.	The RDA One North East used this regional industrial policy to help align the different agendas of HFC stakeholders at the local, sub-regional, regional, national and supranational levels of activity in terms of the resource implications.
Tees Valley Hydrogen Project (TVHP) (2001)	Encourage economic growth and raise educational attainment and skill levels.	A number of HFC demonstration projects in the Tees Valley in the early 2000s involved integration with buildings and monuments that symbolized the region's historical activity in petrochemicals, steel and coal.
Energy Innovation Zone (2001)	Break down socio-economic barriers and build upon local strengths to counteract continuing population and employment decline in the Outer Hebrides.	Public leverage of funding for activity including HFC demonstration work.
The London Hydrogen Partnership (LHP) (2002)	Strategically align public and private actors, legitimise HFCs, facilitate knowledge transfer and de-risk investment with the overall aim of establishing a regional hydrogen economy.	In 2002, the Greater London Authority (GLA) launched the LHP. The long-term aspiration was to contribute to carbon reduction targets and boost the regional economy.

Appendix K: National/Regional Policy Instruments Affecting HFC Innovation and Diffusion in Wales

Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Automotive Strategy (2000)	Continue to develop growth in the Welsh automotive sector.	The significant cluster of vehicle components manufacturers in South Wales wants to be part of future HFC mobility supply chains.
Accelerate Wales (2001)	Use networking as the primary means of knowledge exchange for 35 'lead companies' and a further 300 members.	The success of the Accelerate Wales network would also begin to assist knowledge exchange regarding the potential of future HFC mobility supply chains.
Rural Development Plan (NAfW, 2001)	Offer a recovery plan for the rural economy. Draw on and develop export possibilities from existing renewable resources via 'global showcase'.	Kickstarted targeted HFC policymaking in the UK with references to a potential future hydrogen economy based on the production of hydrogen thermally from woody biomass or from the fermentation of carbohydrate-containing organic matter (Maddy et al, 2003).
A Winning Wales (NAfW, 2002)	Improve international competitiveness. Reduce Wales' regional differentials in growth with the UK. Improve enterprise and innovation. Boost skills and learning	This economic policy, and its successor *Wales, A Vibrant Economy* (2006), looked at numerous ways for the Welsh Assembly to pro-actively support businesses through better coordination and the targeting of sectors.
H2 Wales (GU, 2003)	Develop Welsh industry in technologies related to hydrogen production, storage, distribution and use.	This route map and Glamorgan University research clarified the Welsh Assembly's policy approaches to HFC opportunities. It attempted to align actors, e.g. diversification into crops for hydrogen; construction of networks to work together strategically; develop 'an expert knowledge base to inform industry and to support decision-making in for sustainable energy policy.
A Vision of the Hydrogen Economy in Wales (NAfW, 2004)	Offer a rationale, a timeline and a set of technical, political, economic, social and environmental requirements to achieve a 'successful' hydrogen economy in Wales.	This Glamorgan University report, based on a meeting of HFC stakeholders including policymakers, helped to further develop HFC-specific policy options for the Welsh Assembly Government.
Hydrogen Valley Initiative (NAfW, 2004)	Achieve a zero-emission energy-based economy supported by sustainable business community through the exploitation of leading edge technologies and stimulation of emerging niche markets.	This geographically-focused initiative was a Welsh Development Agency (WDA) project designed to stimulate activity in areas of traditional heavy industry (steel, coal, car manufacturing) many of which had been under threat. Attracting high-tech HFC businesses, especially in the automotive sector, had not been realized by 2012 (although Riversimple would relocate in 2014 to Llandrindod Wells).

Low Carbon Economic Area (2010)	i. Exploit existing hydrogen & alternative fuels expertise. ii. Increase green jobs in the automotive & stationary power sectors. iii. Gain a competitive advantage to attract HFC RD&D investment. iv. Accelerate growth in low carbon industries, skills & supply chains.	This geographically-focused initiative was designed to link the HFC activities of manufacturers and universities in South Wales, Bristol and Swindon into a state-backed cluster. While many of the aims had not been realised by 2012, policy learning between HFC stakeholders was advanced.

Appendix L: National/Regional Policy Instruments Affecting HFC Innovation and Diffusion in Scotland

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Outer Hebrides Structure Plan (2003) / *Outer Hebrides Local Plan* (2008)	Set priorities for economic development and associated land use.	Coordination of public leverage of funding for activity including HFC demonstration work.
Building (Scotland) Amendment Regulations (HMG, 2006, HMG, 2011)	Require regular air conditioning systems inspections. Give advice to occupants on reducing energy consumption.	These regulations have had the potential to encourage HFC RD&D and HFC market development in stationary power.
Scottish Renewables Action Plan (SG, 2009b)	Set out how to meet the Scottish Government's Renewable Energy targets (over 24-36 months).	This plan encouraged HFC RD&D and market development via increased demand for technical solutions to the demand for the localized storage and release of renewable energy.
Climate Change (Scotland) Act (SG, 2009a)	Reduce greenhouse gas emissions and transition to a low carbon economy based on increasing sustainable economic growth. Set target of an 80% cut in GHG emissions in Scotland by 2050.	The Act encouraged HFC RD&D and market development via increased demand for technical solutions to the demand for the localized storage and release of renewable energy.
National Renewables Infrastructure Plan (N-RIP) (2010) (SE/HIE, 2010)	Develop a spatial framework of first phase sites for renewable infrastructure projects.	The plan set in train investment decisions for renewable projects which, once they become facts on the ground, would add to demand for innovation with the localized storage and release of renewable energy.
Non-Domestic Rates (Renewable Energy Generation Relief) (Scotland) Regulations (HMG, 2010)	To permit local authorities to reduce the sums payable in rates for properties in Scotland used for the generation of renewable heat or power (or both).	Although HFC technologies were not identified alongside eligible renewables, this move adds to demand for innovation for the localized storage and release of renewable energy.
Route map for Renewable Energy in Scotland (SG, 2011)	Deliver 100% energy generated by renewables in future via infrastructure delivered through its own planning system.	The route map accelerated the delivery of renewable projects which, as they become facts on the ground, should add to demand for innovation and delivery over time of localized storage and release technologies to complement renewable energy.

Appendix M: Regional Diffusion of HFC Knowledge Development Activity (F2), 1954-2012 (Part 1)

Nation / Region	code	total type	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Northern Ireland	NI	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scotland	SCO	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North East	NE	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North West	NW	annual	0	0	0	0	0	2	2	0	5	6	0	4	1	2	1	1	3	1	0	0
		cumulative	0	0	0	0	0	2	4	4	9	15	15	18	19	21	22	22	25	25	25	25
York & Humber	YH	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
West Midlands	WM	annual	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	1	1	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	2	2	4	4	4	4	5	6	6
East Midlands	EM	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
East	E	annual	1	0	0	0	0	2	0	0	1	0	0	0	1	-1	0	0	0	0	0	0
		cumulative	1	1	1	1	1	3	3	3	4	4	4	4	5	4	4	4	4	4	4	4
Greater London	LON	annual	0	0	0	0	0	2	1	3	1	3	1	0	2	1	2	0	0	3	0	3
		cumulative	0	0	0	0	0	2	3	6	7	10	11	11	13	14	16	16	16	18	18	21
South East	SE	annual	0	0	0	2	1	1	1	2	0	3	3	4	5	2	2	3	2	2	0	1
		cumulative	0	0	0	2	3	4	5	7	7	10	12	16	20	22	24	27	28	30	30	31
South West	SW	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wales	WAL	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
grand totals		annual	1	0	0	2	2	7	4	5	7	11	4	9	8	6	5	3	4	6	1	3
		cumulative	1	1	1	3	5	12	16	21	27	38	42	51	59	65	70	73	77	83	84	87

Appendix L: Regional Diffusion of HFC Knowledge Development Activity (F2), 1954-2012 (Part 2)

Nation / Region	code	total type	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Northern Ireland	NI	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scotland	SCO	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North East	NE	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
North West	NW	annual	1	4	0	2	0	0	0	1	0	0	0	1	4	0	0	2	2	1	0	1
		cumulative	26	30	30	32	32	32	32	33	33	33	33	34	38	38	38	40	42	43	43	43
York & Humber	YH	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
West Midlands	WM	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
East Midlands	EM	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
East	E	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		cumulative	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5
Greater London	LON	annual	0	2	2	2	2	3	3	0	2	3	0	2	3	0	1	0	0	1	1	1
		cumulative	21	23	24	26	28	30	33	33	34	37	37	39	41	41	42	42	42	42	43	43
South East	SE	annual	2	0	2	-2	3	3	0	3	1	1	1	1	1	0	1	0	4	1	3	1
		cumulative	32	32	34	32	34	37	37	39	40	41	42	42	43	43	43	43	47	48	51	52
South West	SW	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Wales	WAL	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
grand totals		annual	3	6	3	2	4	5	3	4	2	4	1	3	7	0	1	2	6	2	4	6
		cumulative	89	95	98	100	104	109	112	115	117	121	122	125	132	132	133	135	141	143	147	153

Appendix L: Regional Diffusion of HFC Knowledge Development Activity (F2), 1954-2012 (Part 3)

Nation / Region	code		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Northern Ireland	NI	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2
Scotland	SCO	annual	0	0	0	0	0	0	0	1	0	1	1	0	0	3	1	4	1	3	1
		cumulative	0	0	0	0	0	0	0	1	1	2	3	3	3	6	7	11	12	15	16
North East	NE	annual	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	2	0	0	0
		cumulative	1	1	1	1	1	1	1	1	1	1	2	3	3	4	5	7	7	7	7
North West	NW	annual	2	0	0	0	1	0	0	1	3	3	0	0	0	3	2	3	5	3	0
		cumulative	45	45	45	45	46	46	46	47	49	52	52	52	52	55	57	60	65	68	68
York & Humber	YH	annual	0	0	0	0	0	0	0	0	3	4	0	1	1	0	1	2	6	3	3
		cumulative	0	0	0	0	0	0	0	0	3	7	7	8	9	9	10	12	18	21	24
West Midlands	WM	annual	0	1	0	0	0	0	1	0	0	1	1	1	2	3	0	5	1	3	0
		cumulative	6	7	7	7	7	7	8	8	8	9	10	11	13	16	16	21	22	25	25
East Midlands	EM	annual	0	6	0	1	1	0	0	2	2	4	3	6	2	0	5	0	3	2	7
		cumulative	1	7	7	8	9	9	9	11	13	17	20	26	28	28	33	33	35	37	44
East	E	annual	0	0	0	0	0	0	0	0	3	0	0	0	0	0	1	1	0	1	0
		cumulative	5	5	5	5	5	5	5	5	8	8	8	8	8	8	9	10	10	11	11
Greater London	LON	annual	0	1	2	0	1	0	0	1	3	1	0	1	0	1	0	2	0	2	3
		cumulative	43	44	46	46	47	47	47	48	51	52	52	53	53	54	54	56	56	58	60
South East	SE	annual	1	2	2	4	2	3	5	3	8	13	11	4	1	7	6	6	7	5	6
		cumulative	53	54	56	60	61	64	69	72	80	94	105	109	110	117	123	129	135	140	146
South West	SW	annual	0	1	1	0	0	0	0	0	0	2	1	0	0	0	3	1	0	4	5
		cumulative	1	2	3	3	3	3	3	3	3	5	6	6	6	6	9	10	10	14	18
Wales	WAL	annual	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0
		cumulative	1	1	1	1	1	1	1	1	1	2	2	2	3	3	4	5	5	5	5
grand totals		annual	*3*	*10*	*5*	*5*	*4*	*3*	*6*	*8*	*20*	*30*	*18*	*14*	*7*	*18*	*21*	*27*	*23*	*25*	*26*
		cumulative	*156*	*166*	*171*	*176*	*180*	*183*	*189*	*197*	*217*	*247*	*266*	*280*	*287*	*305*	*326*	*352*	*376*	*401*	*427*

Appendix N: Entrepreneurial Activity TIS Events (F1) by Region, 1999-2012

Nation/Region	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	total	share
Northern Ireland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
East	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Wales	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	3%
North East	0	0	0	0	0	0	0	0	1	1	0	0	0	0	2	3%
Greater London	0	0	0	0	0	1	0	0	0	0	0	0	1	2	4	6%
Scotland	0	0	0	0	1	0	0	1	0	0	0	3	1	0	6	8%
South West	0	0	0	0	0	0	0	0	0	0	0	0	3	4	7	11%
East Midlands	0	0	0	0	0	0	0	0	0	1	0	2	1	0	4	7%
North West	0	0	0	0	0	0	0	0	0	0	0	2	3	2	7	9%
West Midlands	0	0	0	0	1	0	1	1	2	2	1	0	1	1	10	13%
Yorkshire & Humberside	0	0	0	0	0	0	0	0	0	1	1	2	2	2	8	11%
South East	0	1	0	0	0	0	0	2	3	1	3	4	1	3	18	27%
annual total	0	1	0	0	2	1	1	4	6	8	5	13	13	14	68	100%
cumulative total	0	1	1	1	3	4	5	9	15	23	28	41	54	68	-	-

Appendix O: UK Energy RD&D Spend 1974-2012 (€m 2014 prices)