HubNet Position Paper Series

Integrated energy systems:

An overview of benefits, analysis methods, research gaps and opportunities

Title	Integrated energy systems: An overview of benefits, analysis, research gaps and opportunities
Authors	Muditha Abeysekera, Prof. Jianzhong Wu, Prof. Nick Jenkins
Author Contact	AbeysekeraM@cf.ac.uk
Draft	1.0 (31/11/2015) – First Draft 2.0 (01/05/2016) – Second Draft with Reviewer comments addressed
Status	Draft
Date Issued	
Available from	www.hubnet.org.uk

About HubNet

Hubnet is a consortium of researchers from eight universities (Imperial College and the universities of Bristol, Cardiff, Manchester, Nottingham, Southampton, Strathclyde and Warwick) tasked with coordinating research in energy networks in the UK. HubNet is funded by the Energy Programme of Research Councils UK under grant number EP/I013636/1.

This Hub will provide research leadership in the field through the publication of in-depth position papers written by leaders in the field and the organisation of workshops and other mechanisms for the exchange of ideas between researchers and between researchers, industry and the public sector.

Hubnet also aims to spur the development of innovative solutions by sponsoring speculative research. The activities of the members of the hub will focus on seven areas that have been identified as key to the development of future energy networks:

- Design of smart grids, in particular the application of communication technologies to the operation of electricity networks and the harnessing of the demand-side for the control and optimisation of the power system.
- Development of a mega-grid that would link the UK's energy network to renewable energy sources off shore, across Europe and beyond.
- Research on how new materials (such as nano-composites, ceramic composites and graphene-based materials) can be used to design power equipment that are more efficient and more compact.
- Progress the use of power electronics in electricity systems though fundamental work on semiconductor materials and power converter design.
- Development of new techniques to study the interaction between multiple energy vectors and optimally coordinate the planning and operation of energy networks under uncertainty.
- Management of transition assets: while a significant amount of new network equipment will need to be installed in the coming decades, this new construction is dwarfed by the existing asset base.
- Energy storage: determining how and where storage brings value to operation of an electricity grid and determining technology-neutral specification targets for the development of grid scale energy storage.

The HubNet Association is a free-to-join grouping of researchers and research users. Join via the “HubNet Registration” tab at www.hubnet.org.uk to obtain access to working document versions of positions papers, an archive of workshop and symposium presentations and to receive notification of future events.

Executive summary

Recent analysis of the UK's energy supply system shows that many of the strategies to decarbonise energy will have significant impacts on existing gas and electricity networks, and will lead to the emergence of new energy carrier systems such as district heating and cooling and potentially new infrastructure to support the use of hydrogen. The energy system transition is likely to create a more distributed energy system where local energy generation plays a much greater role in energy supply.

Traditionally, the different energy supply systems i.e. electricity, gas, district heating/cooling and hydrogen had relatively few interactions and were designed and operated independently of each other. However, with increasing interactions between energy systems, there is a significant interest to explore complementarities of integrating energy networks (e.g. Power to gas energy storage and Thermal stores providing demand response).

The drivers for integration between various energy systems are discussed in detail in Chapter 2; in summary these are to:

a) Reduce the use of primary energy
b) Increase the generation and utilisation of renewable energy
c) Reduce/delay capital expenditure
d) Provide cost effective flexibility in the electrical power system
e) Give opportunities for business innovation
f) Increase reliability of the electrical power system (e.g. security of supply)
g) Facilitate low carbon sustainable districts and local governance of community projects

The topic of integrating energy systems has attracted interest from academia, industry and policy makers in different parts of the world. Chapter 3 presents the landscape of research activities in this area. In the UK, the EPSRC, ETI and Energy Systems Catapult have all taken major initiatives to develop expertise in realising the benefits of energy systems integration.

Chapter 4 presents the approaches being developed in academic literature for analysing integrated energy systems. They are categorised and discussed as:

a) Coupled energy network modelling and simulation
b) Operation planning and control (e.g. optimization, demand response)
c) Techno-economic and environmental performance analysis
d) Design and expansion planning
e) Reliability analysis of integrated energy systems.

In spite of the interest and recognized benefits of energy system integration there are significant challenges to realising its potential. The fragmented institutional and market structures in the different energy sectors, the increased complexity of an integrated energy system, not least the multidisciplinary nature of research and development are amongst the numerous barriers.

A number of research gaps and development opportunities collated from a review of the literature and an international stakeholder workshop are listed in Chapter 5. The need to develop robust methods and tools for modelling and analysis of integrated energy systems; develop standardized test systems for integration solutions and demonstration activities can be highlighted.

Contents

This position paper follows a workshop that brought together a group of international researchers to discuss the potential benefits and research gaps in integrated energy systems. The workshop was organised by Cardiff University and held at Imperial College, London on 31st October 2014 as part of the HubNet programme. The workshop minutes are appended.

1. Introduction

1.1 Energy system transitions in the UK

Energy supply systems have undergone numerous transitions over time (Pearson, 2012, Rutter and Keirstead, 2012). These were stimulated by scientific and technological advances (e.g. discovery of electricity) combined with political and socio-economic developments (e.g. urban growth). Some of the recurring themes in each transition were identified in (Rutter and Keirstead, 2012) as:

(a) An increase of per capita energy use (despite increases in efficiency of energy supply technology)
(b) An increase of the energy system's organizational and technological complexity
(c) The correlation in energy system transition to wider changes in society and technology (e.g. increase in transport speeds and rail networks in facilitating urban growth).

Today, in the UK, the energy demands of the domestic, commercial and industrial sectors are largely met by electricity and natural gas. Britain's electricity and gas networks span large areas, knitting cities together into a national and regional energy system that, in the case of electricity in particular, must be balanced on a near-real time basis.

1.1.1 Coupling of electricity and gas networks

The coupling of electricity and natural gas systems is a feature in the UK's energy supply system. The physical integration of the electricity and gas networks was first seen with the 'dash for gas' in the 1990's when newly privatised electric companies were allowed to generate electricity using natural gas (Pearson, 2012). The key drivers for the 'dash for gas' were:

(a) political: the privatisation of the UK electric industry in 1990; the regulatory change that allowed gas to be used as a fuel for power generation;
(b) economic: gas turbine power stations were quick to build in comparison to coal and nuclear power stations, which were higher in capacity but took longer to construct; the decline in wholesale gas prices with the development of North sea gas; the desire of the regional electricity companies to diversify their sources of electricity supply;
(c) Technical: advances in electricity generation technology (CCGT) with higher relative efficiencies and lower capital costs.

The 'dash for gas' drive resulted in a significant increase in natural gas fired CCGT power stations in UK electricity generation capacity (5% in 1990 to 36% by 2011). Natural gas currently provides over 40% of annual electrical energy generation through gas fired CCGT power generation (DECC, 2014b). Natural gas impacts the electricity price as electrical power generation from natural gas is used to meet the peaks in electricity demand (DECC, 2012c). The electricity and natural gas industries are therefore strongly dependent on each other from an economic, technical and regulatory perspective.

1.2 Multi-energy systems

The UK's energy supply systems are undergoing another phase of transition due to raised concerns over climate change, an aging energy infrastructure and rising fuel prices. Improving efficiency in the building stock, new energy carrier systems (e.g. district heating, district cooling), electrification of heating and transport, increasing use of low carbon/renewable energy and the development of smart electrical grids are all parts of concerted efforts to address these concerns.

Recent modelling from the government (DECC, 2013), academia (Hughes and Strachan, 2010), and industry (Nationalgrid, 2013) shows that the transition will have significant impacts on existing gas and electricity networks, and will lead to the emergence of new energy carrier systems such as district heating and cooling and potentially new infrastructure to support the use of hydrogen (DECC, 2013). The transition is likely to create a more distributed energy system where local energy generation plays a much greater role in energy supply (RTP Engine Room, 2015).

The uptake of new energy supply systems is encouraged by different drivers: these can be classified as,

(a) Policy and regulatory framework:
Carbon reduction targets and local air quality policy directives have driven local authorities to impose strict regulations on cutting down emissions from the new build sector. Combined heat and power (CHP) and district heating systems are used by project developers to achieve these regulatory targets.

(b) Sector specific challenges:
Decarbonising transport is a significant challenge. Electric vehicles and/or hydrogen fuelled vehicles are the only available options to improve local air quality levels and reduce the greenhouse gas emissions from this sector.

(c) Financial:
CHP offers an opportunity to increase security of energy supply and reduce energy costs by generating heat and power simultaneously. In many instances the absence of a suitable heat demand is a barrier for the uptake of CHP units. Heat networks aggregate heat demands in a large area and thereby provides a heat sink for distributed CHP systems. Government support schemes encourage local authorities to consider district heating as a potential energy supply option (DECC, 2015).

1.3 Integration of energy systems

Traditionally, the different energy systems i.e. electricity, gas, district heating/cooling and hydrogen had relatively few interactions and were designed and operated independently of each other for the purpose of handling a single energy carrier. However, today, there is significant interest in exploring the synergies between energy networks (e.g. Power to gas energy storage and Thermal stores providing demand response) and implementing such projects. Interactions takes place through the conversion of energy between different energy carriers and its storage in order to provide services and ensure that each is managed in an optimal way. The numerous possible interactions between the various energy systems are shown in Figure 1.1.

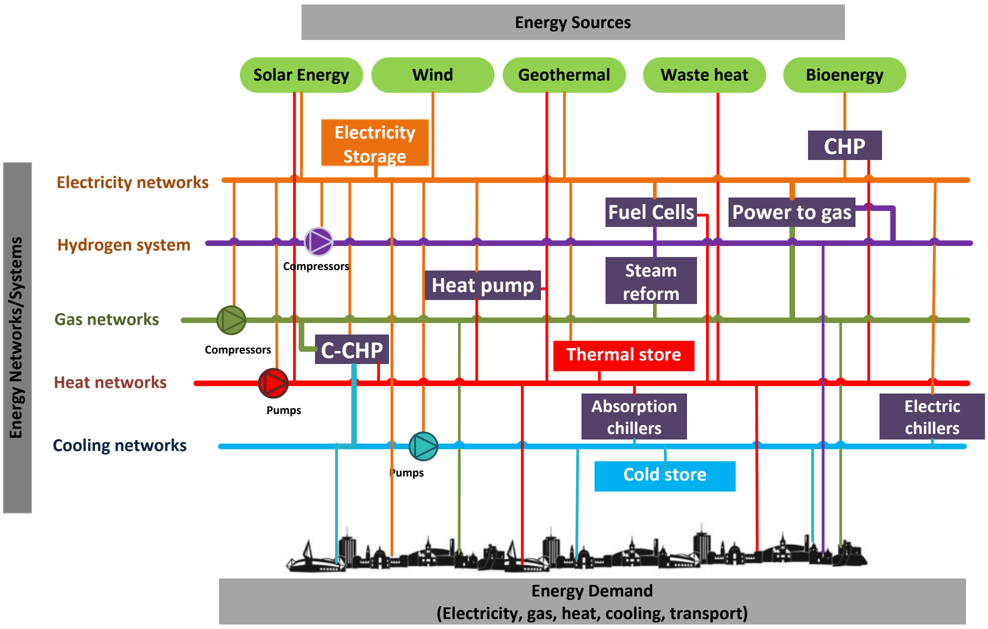


Figure 1.1: Possible interactions between different energy carrier systems and integration of local renewables.

The drivers for integration between various energy systems are discussed in detail in Chapter 2; in summary these are:

a) Carbon emissions reduction
b) Reduction of the use of primary energy
c) Increase of the generation and utilisation of renewable energy
d) Reduction/delay capital expenditure
e) Provision of cost effective flexibility in the electrical power system
f) Opportunities for business innovation
g) Increased reliability of the electrical power system (e.g. security of supply)
h) Facilitation of low carbon sustainable districts and local governance of community projects

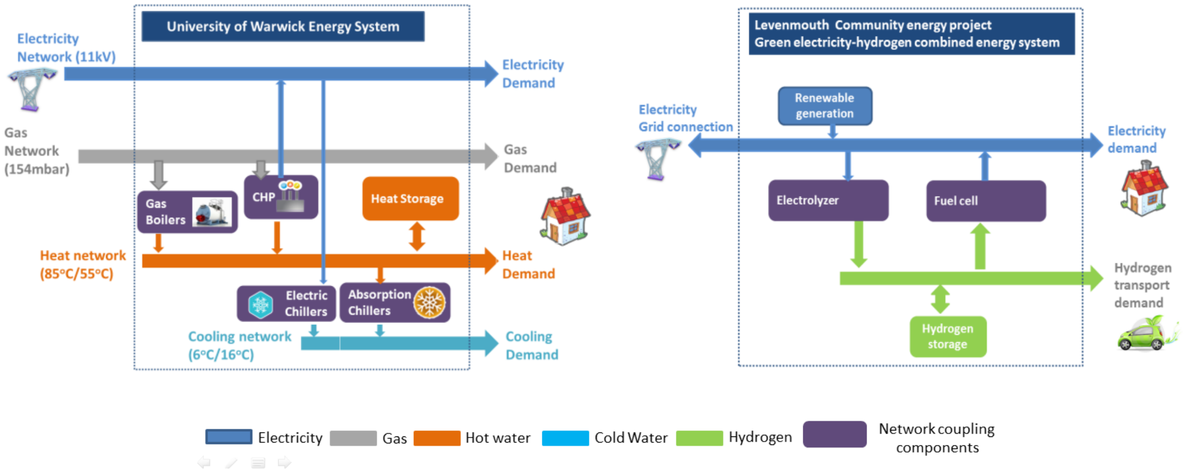
Two practical examples of integration between different energy systems in real community scale energy supply schemes in the UK are shown in Figure 1.2.

Figure 1.2a shows the integrated energy supply scheme at the University of Warwick. Four different energy carrier networks operate to supply the multi-energy demand i.e. electricity, natural gas, district heating and cooling. The different systems are interconnected through,

(a) natural gas fired CHP units simultaneously supplying electricity and heat
(b) gas-fired boilers producing heat to supply the district heating network
(c) absorption chillers producing chilled water by consuming heat from the district heating network
(d) electric chillers producing chilled water by consuming electricity

Figure 1.2b shows the renewable electricity-hydrogen combined energy system at Levenmouth, Scotland. The proposed project is to demonstrate the operation of renewable energy technologies (a wind turbine and solar PV) integrated with an electricity and hydrogen energy system for supplying electrical energy to buildings, energy storage using hydrogen and fuel for hydrogen vehicles. The electricity and hydrogen energy systems are interconnected through,

(a) An electrolyzer that converts electricity from renewable sources to hydrogen in order to supply transport fuel and to store renewable energy
(b) A fuel cell that converts hydrogen to electricity during periods of high electricity demand



(a) Integrated energy supply system at University of Warwick **(b) Green electricity-hydrogen combined energy system**

Figure 1.2: Integration between different energy systems (a) An integrated electricity, natural gas, district heating and district cooling system at the University of Warwick (b) A renewable electricity supply system combined with hydrogen storage, balancing and transport system at Levenmouth, Scotland

1.4 Scope and objective of the paper

This position paper reviews potential techno-economic benefits, the landscape of research activities, analysis methods, research gaps and opportunities in the planning, design and operation of an integrated energy system. A systems approach to energy systems integration (IET, 2014) can enable synergies between energy system to be realised, and conflicts avoided.

The review takes a UK centric approach, however most of the material is applicable to integrated energy systems worldwide. The energy vectors (and their integration) considered in this review study are limited to electricity, natural gas, district heating, district cooling and hydrogen.

2. Benefits of integrating energy systems

The benefits of integrating energy systems were identified from a review of the literature. Figure 2.1 shows the benefits discussed in this paper.

1. Carbon emissions reduction by increasing whole system energy efficiency

2. Increase the generation and utilisation of renewable energy

3. Reduce capital expenditure by increasing asset utilisation and reduce/delay network reinforcements

4. Cost effective provision of flexibility in the electrical power system

5. Opportunities for business innovation

6. Increased reliability of the electrical power system

Figure 2.1: Benefits of integrated energy systems

2.1 Carbon emissions reduction by increasing whole system energy efficiency

A primary driver for the integration of different energy carrier networks is to be able to reduce emissions (and increase energy efficiency) through,

a) co-generation of electricity and heat
b) optimising (in terms of carbon emission and/or costs) the operation of the overall energy system.

2.1.1 Increasing energy efficiency through co- generation

Combined heat and power (CHP) or co-generation systems are widely recognised to have a high potential for improving energy and exergy[1] efficiency compared to the separate production of energy carriers (Horlock, 1987). Figure 2.2 shows an example of energy and carbon emissions savings when supplying a specified electricity and heat demand through a co-generation system compared to the separate production of electricity in a thermal power plant and heat in a gas fired boiler.

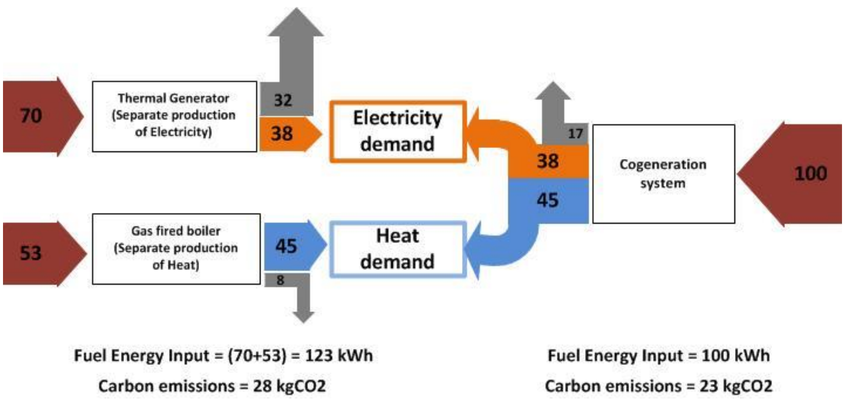


Figure 2.2: Example of energy and carbon emissions saving through cogeneration of electricity and heat (natural gas is assumed as the fuel input in all systems). A carbon intensity of 0.23 kgCO2/kWh for natural gas is assumed; electrical efficiency of thermal generator = 55%; thermal efficiency of gas fired boiler = 85%; electrical efficiency of CHP = 38%; thermal efficiency of CHP = 45% (Horlock, 1987))

[1] Exergy is a concept from the 2nd law of thermodynamics used to characterize the quality of different energy flows. For example, it gauges that the quality of energy in 1kJ of electricity is greater than 1kJ of energy in a waste heat stream (at low temperature).

In thermal power plants for separate electricity generation, a large fraction of the fuel energy is released to the natural environment, mainly through the flue gas and condenser cooling systems (45% in the example above of a CCGT unit). Co-generation systems capture a large part of the otherwise wasted energy in order to supply a local industrial/commercial heat load, or to be used as hot water for district heating. The above example shows that if the use of natural gas is assumed 19% less fuel energy (compared to separate production) is required by a co-generation system to meet the same electricity and heat loads. In the example, the same percentage reduction of emissions (19%) is achieved. A more general discussion on the relationship between fuels, energy savings and emissions reduction through poly-generation systems is available in (Chicco and Mancarella, 2008b). A method for evaluating the value of cogeneration considering the dynamic interactions between co-generation and the centralized electric system was proposed in (Voorspools and Haeseleer, 2003) The co-generation concept is extended as tri-generation or multi-generation according to a number of different energy vectors produced from a single source of fuel. For example, combined cooling, heat and power systems (CCHP) use the heat recovered from electricity generation to supply a heat load and also drive an absorption chiller[2] for cooling. A number of research studies have shown the potential for increasing the energy efficiency of supplying electricity, heat and cooling loads by using CCHP plants (Chicco and Mancarella, 2009, Rezaie and Rosen, 2012, Chicco and Mancarella, 2008a, Mancarella and Chicco, 2008).

In many situations the development of multi-generation systems is hindered by the absence of a suitable load (or market) for some of the different energy products. Multi-energy networks allow the creation of markets by aggregating various energy demands scattered over a wide geographical area. Access to a reliable multi-energy load improves the financial viability and thereby supports the increased uptake of co-generation systems.

2.1.2 Increasing overall energy system efficiency through optimising operation

An integrated system of multi-energy supply networks can use multiple paths to deliver different forms of energy.

For example, Figure 2.3 illustrates the energy supply system at the University of Warwick which comprises electricity, district heating and district cooling networks interconnected through gas fired CHP units, gas fired heat only boilers, electric chillers and heat driven absorption chillers.

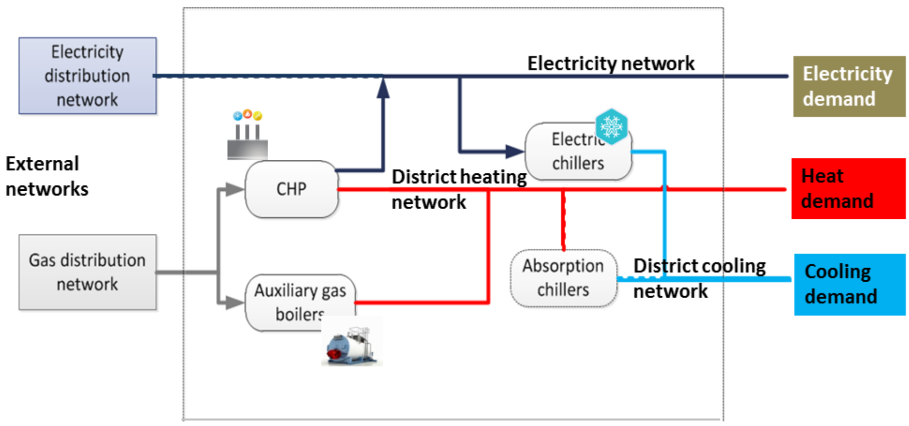


Figure 2.3: Schematic of the integrated energy supply system at University of Warwick

[2] An absorption chiller is a device that uses heat energy to drive the refrigeration cycle for cooling supply.

The multiple supply paths to deliver the different forms of energy loads are,

a) electricity load - through importing electricity from the external grid or from the gas fired CHP generation
b) heat load – through the gas fired CHP generation or gas fired heat only boilers
c) cooling load – through electric chillers or heat driven absorption chillers (connected to the district heating network)

Carbon emissions depend on the amount of electricity and gas consumed from the external grids and the carbon intensity of grid electricity at the time of use. The required amount of electricity and gas from external grids depends on the efficiencies of conversion between different energy carriers. Due to the variations of the carbon intensity of grid electricity and the time-varying nature of different energy loads, multiple supply paths provide an opportunity, to optimise the operation of the energy system, with an objective to reduce carbon emissions. Optimal operation can be encouraged by suitable market instruments (e.g. a carbon tax) that encourages a system wide approach to reducing carbon emissions.

2.2 Increase the generation and utilisation of renewable energy

Progress in developing renewable generation systems is hindered by the lack of cost-effective energy storage capacity and the technical constraints of the existing electricity network (DECC, 2012a). For example, an increase in renewable generation connections may violate the voltage and thermal limits of the electrical network and its components. As a result, when providing a connection, electricity distribution network operators (DNO's) often put forward conditions in the form of:

a) Limiting the capacity of generation that can be connected
b) Contracts that allow tripping/curtailment of the renewable plant in case of network congestion
c) Charging any reinforcement costs of the network to the developer of renewable plant

These conditions are discouraging for a developer who wishes to maximize the economic potential of the investment. They also limit renewable energy generation from sites with the best resource.

There is a potential to increase the generation and utilisation of renewable energy by integrating the electricity network with other energy carriers (Niemi et al., 2012). For example consider the simple schematic of an integrated electricity and hydrogen energy system shown in Figure 2.4.

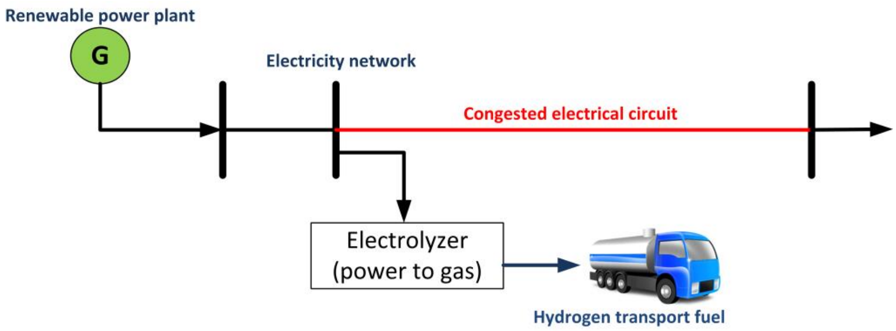


Figure 2.4: Schematic of an integrated electricity and hydrogen energy system for increasing installed capacity of renewable plant

Figure 2.4 shows a renewable generator and an electrolyzer[3] connected to a constrained part of the electrical grid. The electrolyzer can be operated to avoid or reduce violations of the grid constraint. For example the power flow through the congested circuit can be regulated by adjusting the electricity consumption of the electrolyzer. The hydrogen generated is then stored and reconverted to electrical energy or used to supply an alternative use directly (e.g. for transport). This arrangement allows a renewable power plant rated above the grid connection capacity to be installed and thereby captures a larger amount of renewable energy over the year (see Figure 2.5).

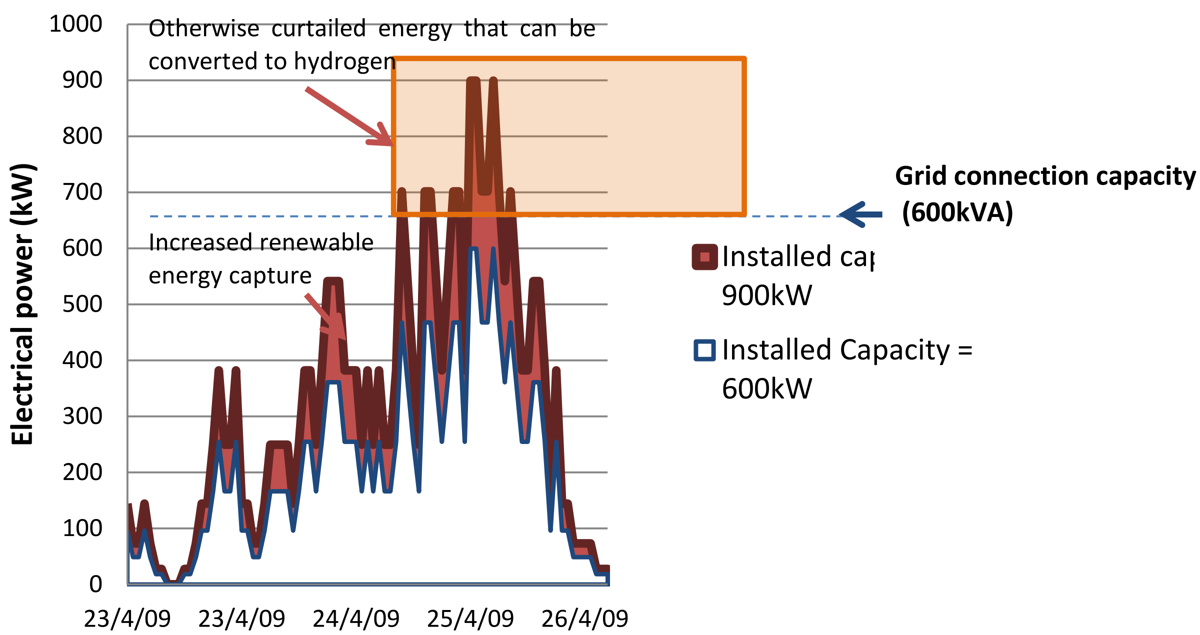


Figure 2.5: The potential for increased renewable energy capture and converting otherwise curtailed energy to hydrogen (Wind data from 23/04/09 to 26/04/09 at a site in mid-Wales)

Figure 2.5 shows a 4-day simulation of the electrical power generated by two different wind turbine installations at a site in mid-Wales. Assuming the DNO specified export capacity at the grid connection point is 600kVA, the maximum capacity of wind turbines in a typical installation is 600kW$_p$. If no other barriers exist (e.g. space, environmental etc.), a larger capacity of wind turbines (900kW$_p$ in the example) allows more renewable electricity to be generated (red shaded area in Figure 2.5). The 900kW$_p$ installation exceeds the grid connection capacity several times during the 4 day period. The excess energy is then converted to a secondary energy vector (hydrogen) and utilised. This allows the electrical grid to absorb a larger quantity of renewable energy while adding an economic value to the energy that would otherwise be curtailed.

A number of research studies have investigated the potential to increase renewable generation by integrating energy systems. The use of electrically heated thermal storage is common in Denmark (Meibom et al., 2013) and electrolyzers are being trialled in a number of demonstration projects across Europe (Gahleitner, 2013). The opportunities for converting excess renewable electricity to a different energy vector only exist due to the present high cost of electrical energy storage at grid scale. The financial attractiveness of using thermal demand and/or electrolyzers for congestion management has yet to be demonstrated as, depending on the costs of equipment and fuel, it may remain more cost-effective to constrain the renewable generation.

---

[3] An electrolyzer produces hydrogen and oxygen from electrical current and a pure water supply through an electrochemical process.

2.3 Reduce capital expenditure

Integration of energy systems can provide additional energy supply capacity (e.g. electricity distribution capacity, energy storage capacity). Investments in upgrading energy infrastructure can be reduced or deferred by

a) Increasing existing asset utilization
b) Reduce/delay network reinforcements

2.3.1 Increasing asset utilization

Asset utilization in energy systems is increased by delivering a larger quantity of energy during their functional life time. The economic advantages of increased asset utilization are:

a) The cost to own equipment is distributed across a larger number of units of energy
b) The payback period of investing in those assets will reduce, which reduces the investment risk

This can be achieved in integrated energy systems through,

a) Sharing energy storage: accessing low cost energy storage available in different energy systems
b) Sharing power generation assets: co-generation of energy vectors
c) Sharing energy transport assets: Shifting energy demand between different energy carrier networks

(A) Sharing energy storage

Periods with excess renewable energy are expected to grow as the UK continues to invest simultaneously in (inflexible) nuclear power generation and intermittent renewables such as wind and solar generation (Strbac et al., 2012). As a result the value of energy storage is expected to increase. However, to date, the cost of grid scale electricity storage is significantly higher than that at which mass deployment can occur[4]. Therefore, it remains more cost-effective to curtail renewable generation when electricity supply exceeds demand (Qadrdan et al., 2015).

On the other hand, energy storage in chemical (natural gas, hydrogen) and thermal energy systems are well developed technologies and relatively inexpensive. Through integration of energy systems, electricity networks can access the energy storage capacity available in other already built energy systems (Vandewalle et al., 2012b). For example, many developed countries have an established gas grid and have access to its large energy storage capacity. GB's natural gas network has a large energy storage capacity due to its linepack mechanism[5] and existing gas storage that can be utilised to store the energy from of excess electrical generation from renewables.

As shown in Figure 2.6, the excess electricity from renewables can be converted to hydrogen and/or synthetic methane and injected in the natural gas grid for storage (termed power to gas) (Grond et al., 2013). Existing gas fired power generators allow the reconversion of gaseous energy to electricity, allowing the renewable energy to be time-shifted. Alternatively, hydrogen and/or synthetic methane can be used as a CO_2 neutral fuel to substitute natural gas in the gas grid and reduce reliance on fuel imports (ITMPower, 2013).

---

[4] Pumped hydro is the only economic form of storing grid scale amounts of excess electricity to date [3]
[5] Line packing is the process of compressing a larger quantity of gas into a pipeline using an increase in pressure

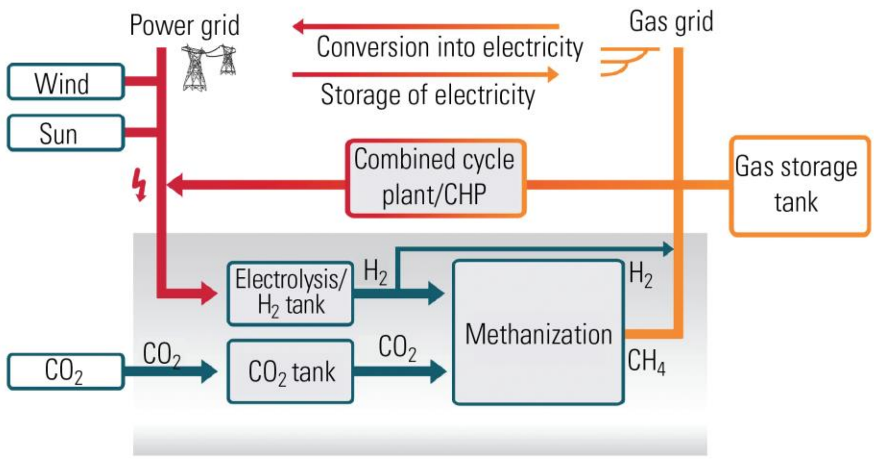


Figure 2.6: Schematic of a power to gas energy storage system (Patel, 2012)

Using spare capacity in the gas network for electricity storage is a potentially attractive solution to the problem of storing excess renewable energy. Germany is pioneering the development of power to gas energy storage systems through several demonstration and commercial projects (Patel, 2012). The main drawback of this type of storage solution is the relatively low round trip efficiency[6] (around 35% for power to gas systems compared to above 90% for battery storage) (Rastetter, 2013).

(B) Sharing generation assets

Generation assets can be shared between different energy systems through co-generation of electricity and useful heat. In the case of tri-generation, the co-generation system can be shared by electricity, heat and cooling systems.

For example an opportunity exists to use co-generation assets to provide balancing capacity to multiple energy systems. At present, they are designed with the aim of supplying a specific heat load. The electricity generated is used to offset grid imports and any excess is exported to the grid. Due to the relatively small capacity as individual units (less than 10MW) and their primarily role in heat load supply, CHP plants are typically not considered reliable sources of electrical power to provide energy to the grid when needed. However, with the use of thermal storage, aggregators[7] and co-ordinated controls, CHP plants can potentially provide balancing services to the electrical grid when required. This can be achieved by, decoupling the time of heat generation from heat demand (using heat storage) and engaging CHP plants in the electricity capacity market actively (Kitapbayev et al., 2014).

(C) Increase utilisation of network assets

The utilisation of network assets can be increased by shifting complementary loads between energy carrier networks. For example, the annual space heating and cooling demand profiles (particularly in northern climates) display a complementary seasonal variation (Frederiksen and Werner, 2013). The assets designed for the supply of heat or cooling demand alone are underutilized. This is a particular

[6] Round-trip efficiency is the amount of energy available when an energy storage system is discharged as a fraction of the energy used for charging. It is a measure of inefficiency of the energy storage system.
[7] In order to meet the minimum volume requirements of providing balancing services to the electricity system operator, smaller sites may be aggregated together with other sites

challenge when considering the large scale investment required in developing district heating/cooling networks.

Network utilization can be increased by combining complementary demand profiles of space heating and cooling to be supplied through a single energy carrier network. This can be achieved by shifting the space cooling load to a district heating network by using absorption chillers (see Figure 2.3). The use of absorption chillers will increase the district heating network load during summer periods (when space heating demand is low). This would increase the average annual energy flow through heat network assets and improve its economic viability for investment.

2.3.2 Reduce/delay electricity network reinforcements

In several parts of GB, the electricity transmission and distribution system is congested due to power flows reaching network design capacities. For example, on occasion, wind generation in Scotland needs to be constrained (Qadrdan et al., 2015). The development of renewable generation and the electrification of heating and transport[8] (increasing network load) requires reinforcement of the congested areas of the network to allow increased power flows through its circuits.

Integrating the constrained parts of the electricity system with other established energy systems provide an opportunity to manage congestion and an alternative means of transporting electricity. For example, Figure 2.7 is a simple schematic of a potential 'power to gas' arrangement to manage congestion in the electricity circuit and increase energy transport capacity in this route.

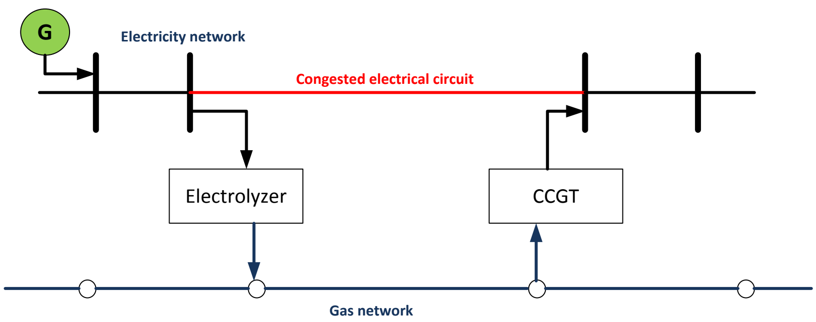


Figure 2.7: A schematic of the 'power to gas' concept for sharing energy transport capacity

During periods when the electrical circuit is congested the electrolyzer absorbs the excess power and produce hydrogen or synthetic methane. The hydrogen or synthetic methane can then be injected in the gas grid to be transported and reconverted to electricity through gas fired power generation. This allows the electricity power flow to bypass the congested circuit. The main drawback in the above solution is again the low round trip efficiency as discussed in section 2.2. Several studies have investigated the feasibility of using the GB natural gas infrastructure for storage and transport of electricity in a future high wind scenario (Qadrdan et al., 2015, Clegg and Mancarella, 2015, Clegg and Mancarella, 2016).

2.4 Cost effective provision of flexibility in the electrical power system

The flexibility of a power system is reflected in its ability to maintain electricity supplies of the required quality in the event of sudden and large variations of generation or demand. For example, to manage generation and demand variations in the short term, quick response generation plants are needed while for longer term variations the ability to store a large quantity of energy is required.

[8] It is expected that the level of electricity consumption will increase due to the expected electrification of heat and transport demand

Flexibility is required increasingly in electricity networks due to the stochastic nature of renewable power that creates discrepancies between generation and demand. Figure 2.7 shows the variation in net electrical load which is defined as the difference between total electricity demand and wind power generation. This difference needs to be supplied using dispatchable plant. A large share of wind generation in the electrical power system causes the following to occur.

- Steeper ramping up and down of the net load will lead to higher rates of increase or decrease in dispatchable power generation.
- During periods of high wind power generation, the dispatchable generators need to turn down their output to low levels but remain available to ramp up quickly when required.
- The net load profile displays peak demands which are short in duration. This results in fewer operating hours for dispatchable plant, affecting cost recovery.

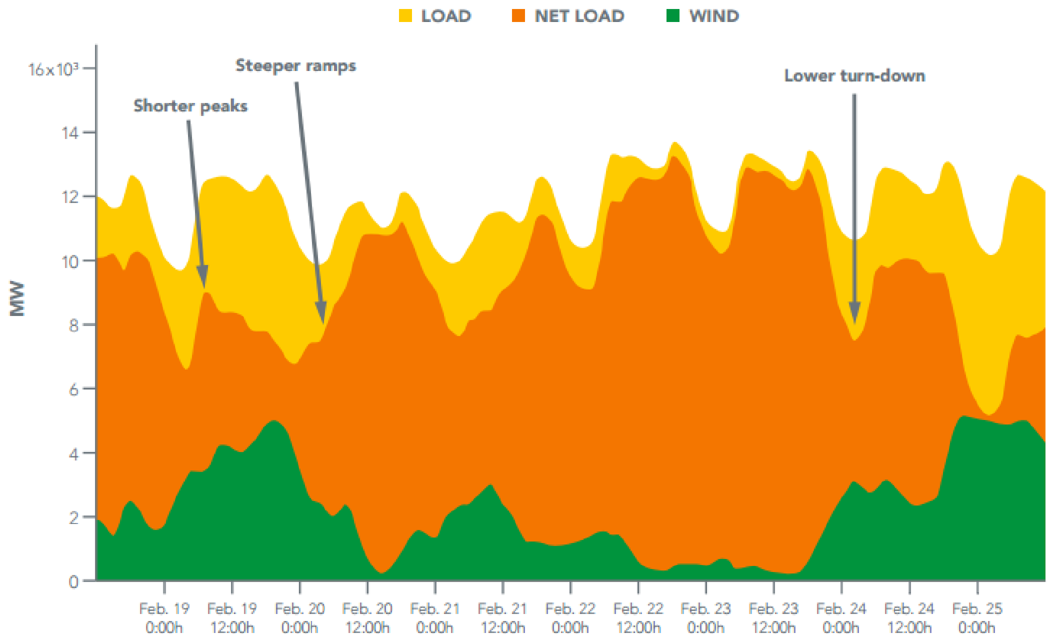


Figure 2.7: Variation in electricity load and renewable generation (Example from utility in the western U.S.)(21st Century Power Partnership, 2014)

Integration with other energy systems can provide flexibility to the electrical power system by,

- shifting electrical load between different energy systems
- providing access to a large pool of smaller sized quick response generation plant

The following example is used to illustrate flexibility provision in the electrical power system through integrated energy systems. Figure 2.8 shows multiple, integrated energy systems connected to the main electricity and gas grids. In each sub-system, the electrical load is supplied through the import of electricity from the main grid and/or generation from the local gas fired CHP. The heating load is met through a heat network supplied by the CHP coupled with a heat storage system. The cooling load is met through a chilled water network supplied from electricity driven chillers and/or heat driven absorption chillers coupled with a cold storage system.

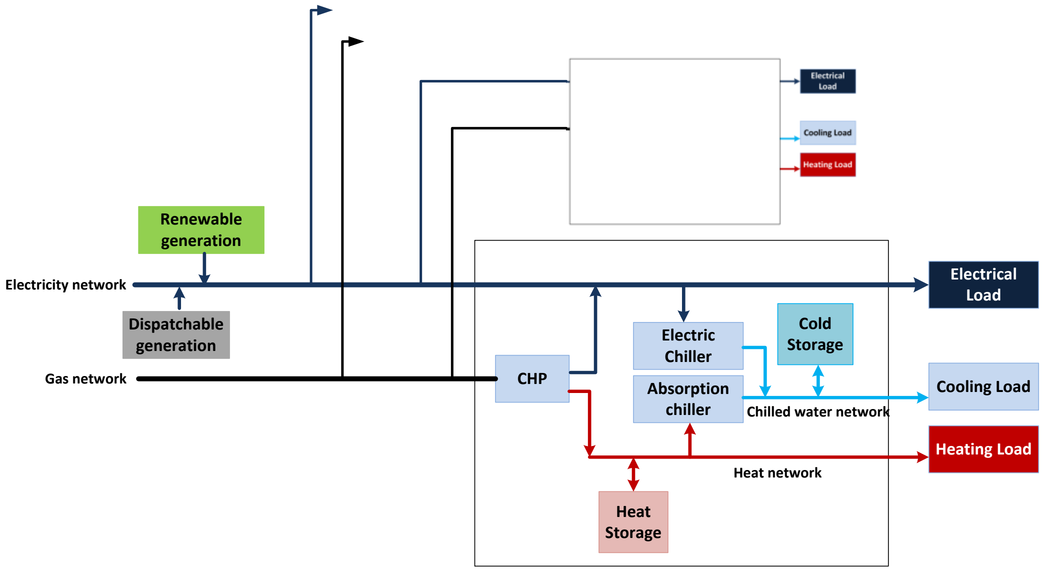


Figure 2.8: Schematic of multiple integrated energy systems connected to electricity and gas grids

In the event of a sudden increase in renewable generation coinciding with a low electricity load (steep ramp down in net load), the gas fired CHP unit reduces its generation output to balance the electrical power system. At the same time electric chillers are switched on (if switched off) to increase load. The heat and cold storage units allow the CHP unit and chiller operation to be decoupled from time of demand. Similarly, during a sudden loss of power generation in the main grid (steep ramp up in net load) the small scale gas fired CHP units increase generation rapidly. Simultaneously, the cooling load is shifted to the heat driven absorption chillers so reducing electrical load. On both these occasions, provision of flexibility to the electrical power system is achieved without any supply disruption to the final consumer.

The development of these flexibility services depends on an adequate communication and control infrastructure which for such small scale units may be expensive. The role of aggregators will be important to manage and provide a sufficiently sized response to the power system operator.

2.5 Opportunities for business innovation

Integration of energy systems creates new opportunities for partnerships between traditionally separate energy businesses. For example, the integration between electricity and hydrogen energy systems through power to gas systems could facilitate partnerships between the electricity and transport sectors and the uptake of hydrogen vehicles (Rastetter, 2013, Cipriani et al., 2013). Integration of systems would enable better co-ordination and planning of technical and commercial processes. For example, a fleet of hydrogen vehicles could plan its re-fuelling strategy in a way that complements power system operation. Potentially, this would lead to an overall cost reduction in power generation and supply. A large number of demonstration and commercial projects are investigating the business opportunities in integrating energy systems processes.

Integration of energy supply systems creates new opportunities for businesses to diversify products and services in the energy sector. Diversification of products/services provides an additional income or lowering the average cost for a firm to produce two or more products. For example, consider a conventional CHP plant that is heat demand driven. Through better co-ordinated control combined with heat storage, the CHP plant can actively participate in electricity load/demand balancing (Cardell, 2007). This would provide an additional revenue stream for the CHP owner and flexibility for the power system operator. A business case analysis of flexible multi-generation options was investigated in (Capuder and Mancarella, 2014b).

Integration of energy systems can also assist developing new markets in the energy sector. For example, the market for hydrogen can benefit from the numerous opportunities for hydrogen generation and consumption in an integrated energy system (Rastetter, 2013). New business models and innovative processes can be introduced to take advantage of the emerging markets. This would potentially increase market competition across different energy sectors bringing value to the final consumer (Good et al., 2016).

2.6 Increase reliability of the electrical power system

Typically, energy supply systems are built with a certain level of redundancy (both generation and transport) to ensure reliable supply of energy. The interconnection of different energy systems makes it possible to supply a load from several different paths. For example, gas fired power generation establishes a connection between the electricity and gas network and when managed properly can improve the reliability and availability of electricity supply. However, the loads from the electrical network will migrate to the gas network, resulting in a more intensively used gas network. Reliability considerations in integrated energy systems were investigated in (Koeppel, 2007).

Another method to increase reliability is to enable parts of the electrical system to operate in islanded mode during events like faults and voltage fluctuations in the main grid. These sections of the network are able to increase the penetration of renewable resources and improve reliability through distributed local control in connection with the main grid or in an intentional islanded mode during supply interruptions. Multi-energy microgrids are gaining research interest due to the number of ways to balance multi energy supply and demand (Kyriakarakos et al., 2011, Kyriakarakos et al., 2013).

However, increased interdependency between energy systems can create a system that is more susceptible to cascaded failures (Rinaldi et al., 2001, Almassalkhi and Hiskens, 2012). Detailed modelling and analysis is required to identify the advantages and disadvantages of certain interconnections between networks.

3. Landscape of research activities

The benefits of integrating energy systems have attracted interest from academia, industry and policy makers in different parts of the world. For example, the European Commission's Strategic Energy Technology plan (SET plan) (European Commission, 2015b) highlights the importance of interoperability between different energy networks and a holistic approach to energy system optimisation. In 2013, the US Department of Energy's National Renewable Energy Laboratory (NREL) opened an Energy Systems Integration Facility (ESIF) at a cost of US$135 million (Kroposki et al., 2012). In 2013, IEEE Power and Energy Magazine published a special issue in energy systems integration (IEEE, 2013). The Journal of Applied Energy has recently commissioned two special issues titled 'Integrated Energy Systems' dedicated to this particular area of research (Applied Energy, 2015).

A number of titles are used to describe the area such as 'energy systems integration, 'multi-energy - carrier networks', 'multi-vector energy systems' and the 'energy internet'.

3.1 UK research landscape

In the UK, early interest in studying interdependencies of different energy systems was due to its interconnected electricity and natural gas systems. However, the challenges of decarbonising heat, cooling and transport have recently fuelled an interest in the interactions between different energy systems (DECC, 2013).

Contrary to its earlier emphasis on the electrification of heat (DECC, 2012b), recent UK Government strategy promotes heat networks, particularly in urban areas. The Department of Energy and Climate Change (DECC) published the policy papers 'Future of heating' (DECC, 2013) and the 'Community energy strategy' (DECC, 2014a) which emphasise support for district heating. It is now expected that the gas network will continue to play an important role during the transition to a low carbon energy system with an increased use of renewable gas (e.g. biogas, synthetic methane). The use of hydrogen as an energy vector for industrial heating and transport has also been highlighted.

The UK has a number of funding mechanisms supporting RD&D in integrated multi-energy systems from an early stage through to demonstration. Figure 3.1 shows the main funding organisations and their stages of engagement.

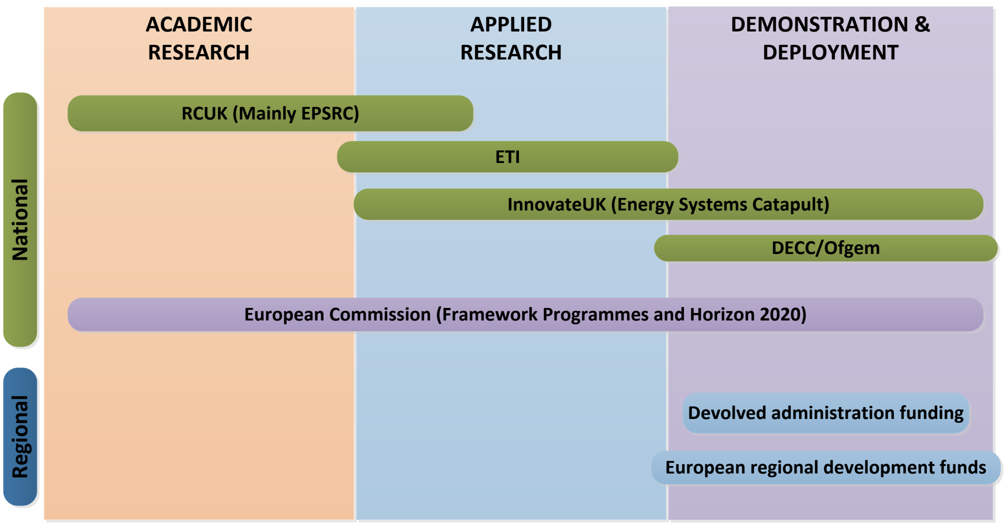


Figure 2: UK Integrated energy systems research funding programmes from academic research through to demonstration

3.1.1 Academic research in the UK

The Engineering and Physical Sciences Research Council (EPSRC) is the UK's main agency for funding academic research in engineering and physical sciences. Details of EPSRC funded research projects that investigate interactions and interdependencies between different energy systems are provided in Appendix 1. Several of the main projects are listed below.

The UK Energy Research Centre (UKERC) funded by the Research Councils UK (RCUK) Energy programme carried out pioneering work on analysing the interdependencies between GB's electricity and gas systems (UKERC, 2014b). A modelling tool for the optimisation of GB's combined gas and electricity network operation (CGEN) was developed through UKERC funding (Chaudry et al., 2008). Ongoing research programmes at UKERC investigates the interactions, synergies and potential conflicts between electricity, hydrogen and heat vectors at multiple scales of the energy system (i.e. local, national and European).

The HubNet research programme funded by the EPSRC (HubNET, 2015) includes a dedicated research theme for multi-energy systems. The theme aims at developing new modelling and analysis techniques for optimal coordination and planning of integrated energy systems.

The EPSRC Grand Challenge programme Transforming the Top and Tail investigates interactions between different energy vectors at multiple scales of the energy system. For example, the role of European gas supplies in the UK's energy security is being investigated. HubNet and Transforming the Top and Tail projects are collaborations between multiple UK universities and industrial partners.

EPSRC recently funded a research programme titled MY-STORE (Multi-energy storage-social, techno-economic, regulatory and environmental assessment under uncertainty) to investigate the technical, economic, regulatory and environmental performance of multiple forms of energy storage. The project expects to examine opportunities in integrated energy systems to provide multi-energy storage options.

Several EPSRC funded whole energy system research consortiums such as ITRC (ITRC, 2015) and WholeSEM (wholeSEM, 2015) are investigating the interaction and interdependencies of national infrastructure such as electricity, gas, transport, water, waste and ICT using detailed models.

3.1.2 Applied Research in the UK

In the UK, the Energy Technologies Institute (ETI) and InnovateUK (previously the Technology Strategy Board) bring together academia, industry and the Government to accelerate the development of low carbon technologies through investment and targeted innovation calls. Integrated energy systems are emerging as a strategic area of interest in both these organizations.

Energy Technologies Institute (ETI)

ETI is a public-private partnership between global energy and engineering companies[9] and the UK Government (ETI, 2015). Several technology programmes in ETI (Distributed Energy, Smart Systems and Heat, Energy Storage and Distribution) have investigated the role of the electricity, gas and heat sectors in the low carbon transition.

[9] The companies part funding ETI are BP, Caterpillar, EDF, Rolls Royce and Shell

The Smart Systems and Heat programme (SSH) investigates the interactions between different energy vectors and system components in the optimal generation and distribution of heat (ETI, 2014). The SSH programme has recently transitioned to the Innovate UK's Energy Systems Catapult (discussed below). A project under the Energy Storage and Distributed Energy programme titled 'Gas vector pathways development' investigates implications and challenges of transporting novel gases (e.g. hydrogen and synthetic natural gas) through the gas grid.

The Energy System Modelling Environment (ESME) program developed at ETI is a powerful energy system model for the UK (Heaton, 2014). Its whole system scope includes all major flows of energy and interactions between different energy sectors. ESME has been used in a number of research projects including UKERC's 'Energy strategies under uncertainty'(UKERC, 2014a, Pye et al., 2015).

InnovateUK

InnovateUK brings together academia and industry to realise opportunities in science and technology through targeted funding competitions. It is sponsored by the Department for Business, Innovation and Skills.

The Energy Systems Catapult was set up by InnovateUK to develop a network of specialist companies, and serve as an independent source of specialist knowledge on the transformation of heat, gas and electricity networks (InnovateUK, 2015a). The scope of the Energy Systems Catapult includes system design, interoperability, and integration of ICT, data analytics and storage as well as the integration of electricity, gas and heat networks. The Energy Systems Catapult is to deliver Phase one of the ETI's SSH programme as its first major project for the energy industry. Phase one of the project is to work with three local authorities in the UK (Bridgend, Manchester and Newcastle) to realise local area energy plans.

The following are some of the InnovateUK funding competitions that considered innovation in integrated energy systems within its scope.

- Localised energy systems – a cross sector approach (2014): The competition promoted the integration of different energy systems, at a scale from clusters of buildings up to whole districts. The details of projects funded are available at (InnovateUK, 2014)
- Integrated supply chains for energy systems (2015): The competition invested in innovative projects that addressed the challenges in integration of new energy supply and demand side technologies. The details of projects funded are available at (InnovateUK, 2015b)
- Cities integrated by design – (2015/16): The competition intends to invest in technical feasibility studies that examine integrating new or retrofit infrastructure projects into other urban systems in a beneficial way.
- Energy catalyst – (2015/16): The competition funds projects from early concept stage through to pre-commercial technology validation that incorporates integrated whole-system approaches. The scope of the competition includes electricity and heat networks and their systems integration as a specific theme.

3.1.3 Demonstration projects in the UK

In the UK, demonstration projects traditionally demonstrate the benefits of innovation to an individual energy sector (i.e. electricity, heat or transport). This is largely due to the existing regulatory and market structure that defines clear boundaries between each energy sector. For example, Ofgem's[10] Network Innovation Competitions (NIC) (Ofgem, 2015) fund electricity and gas network companies independently to deliver innovative projects that can demonstrate benefits to its customers. DECC's Heat Network Delivery Unit (DECC, 2015) provides grant funding and guidance to local authorities to realise heat network schemes.

Nevertheless, a number of demonstration projects that consider multiple energy systems and their interactions have been developed through community initiatives. Support from European regional funding programmes and the Devolved Administrations is evident in the development of demonstration projects.

3.2 European research

The European Commissions' (EC) research and innovation programme Horizon 2020, includes a number of funding calls related to the integration of energy systems. Details of the Horizon 2020 work programme for 2016-2017 is available at (European Commission, 2015a). For example, the call for low carbon energy includes a competition to promote technologies, tools and/or services that demonstrate synergies between energy networks (LCE-01-2016-2017).

INSIGHT_E, an energy think tank which informs the EC, published a policy briefing paper in 2014 on the synergies of integrating energy networks for electricity, gas, heating and cooling (Brodecki et al., 2014).

The European Energy Research Alliance (EERA) has initiated the development of a Joint Programme[11] focused on energy systems integration (EERA, 2015). The Programme once operational will bring together research organisations in European countries for shared priority setting and collaboration on research projects.

The research programme 'Vision of future energy networks (VoFEN)' led by ETH-Zurich was a pioneering project in developing frameworks and analysis methods in integrated multi-carrier energy systems (Favre-Perrod et al., 2005). The concept of an energy hub was developed and used in methods for economic dispatch, optimal power flow and reliability analysis in integrated energy systems.

Scandinavian countries such as Sweden and Denmark have advanced RD&D in integrated energy systems. They are extensive users of co-generation systems coupled to district heating networks. Denmark for example, has approximately 60% of its heat supplied through district heating systems, a high proportion of wind power (over 30% wind energy on an annual energy balance) and a nationwide natural gas system. The status of RD&D in Denmark is discussed in (Meibom et al., 2013).

Germany is undertaking research and development of power-to-gas energy systems. They are driven by the need for balancing high levels of renewable generation and a demand for electricity storage media. A number of power-to-gas demonstration plants are being developed across Germany for various applications as shown in (European Power to Gas, 2015).

[10] Office of gas and electricity markets

[11] There are 15 EERA Joint Programmes (JP's) established in a wide range of energy research fields. Joint Programmes are aligned with the priorities defined in the SET-Plan for low carbon technology development.

3.3 Other activities

The International Institute for Energy Systems Integration (iiESI) was established as a global institute aimed at supporting education, internships and collaboration opportunities in this research area. This was an initiative sponsored by a group of US and European entities including NREL, Pacific Northwest National Laboratory, the Electric Power Research Institute, University College Dublin and Technical University of Denmark. Several educational workshops have been held in the USA and Europe to address concepts of energy systems integration from technical, market and regulatory perspectives. The workshop programmes and presentations from speakers are available at (iiESI, 2015a). The iiESI also organized a workshop on the key research challenges of energy systems integration in March 2015. The workshop brought together an experienced group of international researchers with a diverse range of expertise. Minutes from the workshop are available at (iiESI, 2015b).

NREL's Energy Systems Integration Facility is pursuing research and development that considers interactions between electricity, thermal, fuel, data and information networks (NREL, 2015a). A white paper was published by NREL in 2012 (Kroposki et al., 2012). The Energy Systems Integration Facility (ESIF) at NREL houses a hardware-in-the-loop system, electrical power system simulator, a thermal distribution system, fuel distribution system, SCADA system and facilities for interconnection and systems integration testing. Details of the facilities at ESIF are available at (NREL, 2015b).

The International Energy Agency (IEA) published a report on the benefits of linking heat and electricity systems through co-generation and district heating and cooling systems. The report is available at (IEA, 2014).

A presentation delivered at the HubNet Smart Grids Symposium 2015, provided an overview of the ongoing research programmes, their objectives and the demonstration activities in integrated energy systems in China. The presentation is available at (HubNET). Integrated energy systems have attracted significant interest in the Chinese government's urban development drive with over £600million R&D funding in 2013.

4: Analysis of integrated energy systems

The literature on the analysis of integrated energy systems can be categorised as the following types:

f) coupled energy network modelling and simulation
g) operation planning and control (e.g. optimization, demand response)
h) techno-economic and environmental performance analysis
i) design and expansion planning
j) reliability analysis

Table 4.1, provides examples of research questions in each of the areas of study.

Table 4.1: Research questions in the analysis of integrated energy systems

<table>
<tr><th colspan="2">Problem type</th><th>Example research questions</th><th>Example studies</th></tr>
<tr><td colspan="2">Network modelling and simulation</td><td>What is the steady state and dynamic behaviour of an integrated energy system under different operating conditions?</td><td>(Liu, 2013, Xu et al., 2015a)</td></tr>
<tr><td rowspan="4">OPERATION & CONTROL</td><td>Operation optimization</td><td>What is the optimal way to operate integrated energy systems to meet a particular objective of the overall energy system (e.g. cost minimization, CO_2 minimization)?</td><td>(Geidl and Andersson, 2007)</td></tr>
<tr><td>Control</td><td>How can the optimal control of integrated energy systems be achieved?</td><td>(Xu et al., 2015c)</td></tr>
<tr><td>Real time demand response and ancillary services provision</td><td>What are the potential opportunities to participate in real-time demand response and ancillary service markets through integrating energy systems?</td><td>(Mancarella and Chicco, 2013a)</td></tr>
<tr><td>Interdependencies (Synergies/Conflicts)</td><td>What are the operational interdependencies that may occur from the integration of energy systems?</td><td>(Qadrdan et al., 2013)</td></tr>
<tr><td colspan="2">Performance analysis</td><td>What is the energy, economic and emissions performance of an integrated energy system?</td><td>(Capuder and Mancarella, 2014a)</td></tr>
<tr><td rowspan="2">DESIGN</td><td>Green field design</td><td>What is the most cost effective structure and sizing of the system components to meet the multi-energy demand?</td><td>(Geidl and Andersson, 2006)</td></tr>
<tr><td>Expansion planning</td><td>What is the optimal way to invest in the expansion of energy infrastructure considering the future multi-energy demands?</td><td>(Chaudry et al., 2014, Martinez Cesena et al., 2015)</td></tr>
<tr><td colspan="2">Reliability of supply</td><td>What is the expected reliability of supply in the event of a failure in an integrated energy system?</td><td>(Koeppel and Andersson, 2009)</td></tr>
</table>

4.1 Integrated energy system modelling and simulation

Traditionally, the modelling of energy networks and simulation is carried out for each energy carrier system independently. To understand the interactions between various energy systems and to design effective control strategies, integration of the different models of each energy system and simulations performed as a combined system are required.

Integrated energy network modelling and simulation studies can be undertaken to investigate the steady-state and/or dynamic behaviour of the combined system.

4.1.1 Steady state modelling and simulation of coupled energy systems

Steady state modelling is undertaken to analyse a system when it is in a state of equilibrium (i.e. the operational parameters do not vary with time). For example, when the volume flow rate of gas through a gas pipe or electrical power flow through a circuit is in steady state the properties of gas flow (pressure) and electricity (voltage magnitude and angle) do not change in time.

Several studies have investigated the integrated modelling and simulation of the electrical network coupled with other energy systems in steady-state. Integrated modelling and analysis of coupled electricity and gas networks in steady state was investigated in (Martinez-Mares and Fuerte-Esquivel, 2012) . Combined modelling and analysis of coupled electricity and heat networks with CHP units and heat pumps was studied in (Liu, 2013). The simultaneous analysis of coupled electricity, gas and heat networks was investigated in (Abeysekera and Wu, 2015, Liu and Mancarella, 2015).

4.1.2 Dynamic modelling and simulation of coupled energy systems

The steady state assumption neglects the significant distinction to be made in the dynamic behaviour of coupling components and different energy carrier types. For example, gas and thermal energy systems have much slower travelling speeds of energy and a larger storage capacity within the transport infrastructure compared to electricity. Dynamic models are important to understand the interactions between different systems and to characterise the propagation of transients from one system to another during normal and abnormal operation.

The integrated modelling and simulation of coupled energy systems considering their transient characteristics is an underdeveloped area of research. Pioneering work was carried out in (Xu et al., 2015a) where dynamic models of coupling components (microturbines and electricity/heat storage) and energy carriers were used to analyse the interactions between electricity and natural gas networks in a microgrid.

4.2 Operation and control of the integrated energy system

Similar to network modelling and simulation, operation analyses are normally carried out independently for each energy carrier system. Increasing interactions and interdependencies between different energy systems require new methods of analyses to ensure reliable and efficient operation of the integrated energy system. The different types of operation analyses undertaken in integrated energy systems literature can be categorised as,

- operation scheduling/optimization
- control of integrated energy systems
- flexibility provision (real time demand response and ancillary services)
- interdependencies analyses

4.2.1 Operation scheduling/optimization

Operation scheduling practices, planning timeframes and modelling tools used for operation optimization vary in different energy systems. For example, the electricity sector uses a half hour balancing period while the gas transmission system typically uses a 24 hour balancing period (Nationalgrid, 2008).

A number of studies examine the extension of traditional concepts used in the electrical power system to the operation scheduling of interconnected energy systems, such as,

- Economic dispatch
- Optimal power flow analysis
- Unit commitment

a) Economic dispatch in integrated energy systems

A method for optimal power generation and energy conversion in a coupled multi-energy carrier system that uses the energy hub concept (see Figure 4.1) was introduced in (Geidl and Andersson, 2008). It is a modification of the classical economic dispatch method in electrical power systems (Wood and Wollenberg, 1984) to account for the different energy demands (i.e. electricity, gas, heat and cooling) and energy conversion between different energy carrier systems. The method is widely used in research related to the operation and design optimization and control of integrated energy systems (Geidl and Andersson, 2006, Xu et al., 2015c).

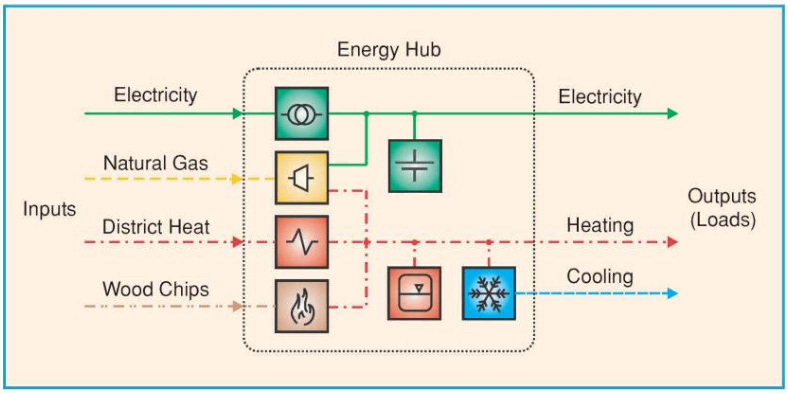


Figure 4.1: Example of an energy hub that contains a transformer, a microturbine, a heat exchanger, a furnace, an absorption chiller, a battery and a hot water storage (Geidl, 2007)

b) Unit commitment in integrated energy systems

The unit commitment problem in electrical power systems is to obtain the optimal start up and shut down schedule for electricity generation plant to satisfy the forecasted demand profile considering cost and constraints such as ramp rates and part load efficiencies (Wood and Wollenberg, 1984). In integrated energy systems context it refers to the optimal start-up and shut down of each plant component to supply multi-energy demand. The role of energy storage is an important consideration for unit commitment in integrated energy systems.

A framework for the unit commitment problem that uses the energy hub concept was proposed in (Ramirez-Elizondo and Paap, 2009). The electricity and heat storage scheduling was investigated as part of the unit commitment problem in (Ramirez-Elizondo et al., 2010). A comparison of using an energy or exergy based approach for unit commitment was undertaken in (Ramirez-Elizondo et al., 2013).

c) Optimal power flow in integrated energy systems

In electrical power system studies, the optimal power flow (OPF) considers the generation dispatch that satisfies the constraints of the transmission system (e.g. operational voltage range, thermal limits of circuits and transformers) while minimising costs (Wood and Wollenberg, 1984). It combines the economic dispatch calculation with the steady state power flow equations and solves them simultaneously. OPF in an integrated energy system considers the supply of multi-energy demands using multiple energy sources and energy conversion units while complying with transmission system constraints in each energy carrier system (see Figure 4.2).

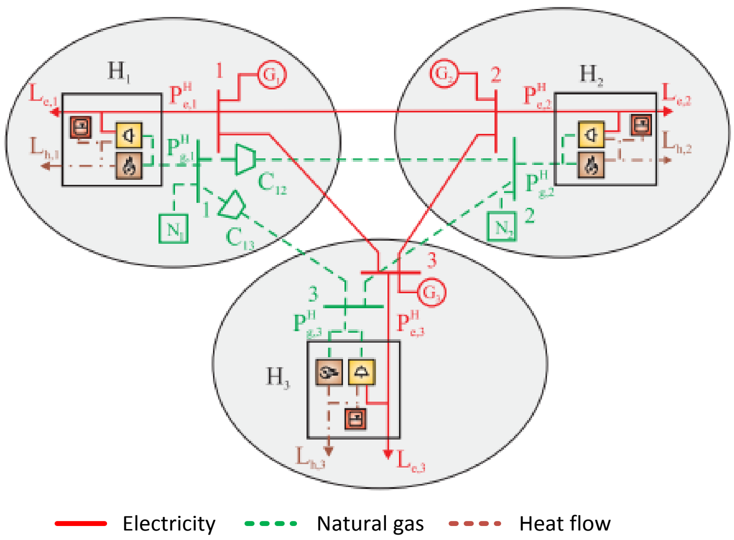


Figure 4.2: System setup of three interconnected energy hubs (Arnold et al., 2010)

The optimal power flow of coupled electricity and natural gas systems was investigated in (Seungwon et al., 2003). The mathematical model of this problem is an optimization problem where the objective function is to find operational set points of the different components that minimize the electricity and gas system operation cost and does not violate the electricity and gas transmission system constraints. A method for optimal power flow computation in coupled electricity, gas and heat systems was developed in (Geidl and Andersson, 2007) where they extend the power system OPF formulation and the Kuhn Tucket optimality conditions to the multi-carrier case.

Multi time period optimal power flow investigates operation planning for a specified time horizon. A modelling framework for ‘time co-ordinated optimal power flow’ in the operation of natural gas and electrical infrastructures under the presence of distributed energy resources was presented in (Acha, 2013),Due to the slow travel speeds and inherent storage characteristics in gas and thermal energy systems it is important to account for the dynamic behaviour of these energy systems in multi time period operation and planning. A method for optimal power flow and scheduling of combined electricity and natural gas systems with a transient model for natural gas flow was investigated in (Liu et al., 2011). Numerical examples were used to compare the solutions for steady-state and transient models of natural gas transmission systems. A multi-time period optimal power flow model was developed for the combined GB electricity and gas networks in (Chaudry et al., 2008) and (Clegg and Mancarella, 2014).

4.2.2 Control of integrated energy systems

The control of integrated energy systems can be categorised into centralized or distributed architectures.

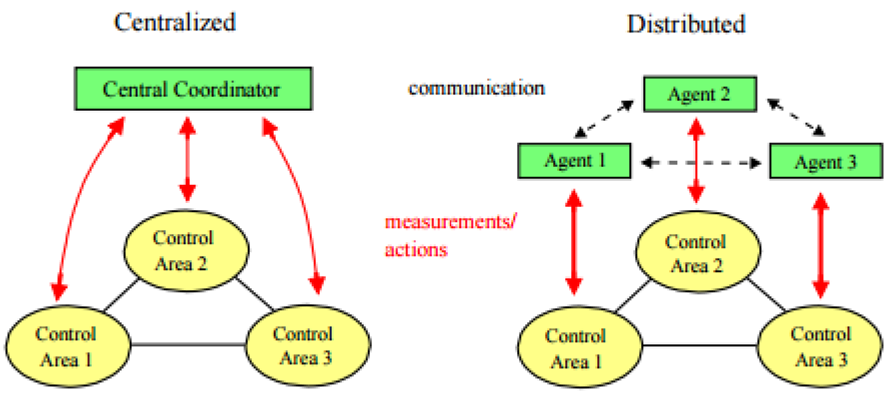


Figure 4.2: Illustration of a centralized and distributed control architecture (The solid arrows refer to communication of measurements/control actions between the physical system and the control unit(s). Information exchange between control units is indicated by dashed arrows)

a) Centralized control

A centralized controller measures variables in the multiple energy networks and determine actions for all actuators in the integrated energy system. In a centralized controller (see Figure 4.2) the optimization and control problems are solved by a single control agent.

A centralized controller that uses a model predictive approach to control (MPC) integrated energy systems was investigated in (Arnold et al., 2009). The controller determines actions for each energy hub that gives the best performance based on steady state behaviour of the transmission system, the dynamics of storage devices and the load and price predictions.

A hierarchical centralized control for an integrated energy microgrid was proposed in (Xu et al., 2015b). The controller incorporates transient characteristics of natural gas flow and the dynamics of energy converters. In order to accommodate the dynamic characteristics of different systems the controller was decomposed into three sub-layers: slow, medium and fast. The control of actuators during fluctuations of renewable power, start-up of an air-conditioner and a microturbine, demand response and energy storage saturation was investigated. The study was extended to the control of an integrated community energy system in (Xu et al., 2015c).

A strategy for the real time control of a coupled electricity and heat system was proposed in (Velez et al., 2011). The control strategy has a hierarchical, centralized architecture and aims to maintain the electricity system frequency at 50Hz and the temperature of district heating water supply at 100°C. A scheduling framework was also presented in (Ramírez-Elizondo and Paap, 2015) where optimization is carried out for a period of 24 hours and the real-time control strategy compensates for the mismatches between the scheduled load and the real load by means of control actions.

b) Distributed control

Even though a centralized control architecture may give the best overall performance, practical and computational difficulties restricts it from being applied in practice. Distributed control architectures decompose the overall optimization and control problem in to sub-problems that are solved using part-models of the system. However, a local control action to be taken depends on the actions of the surrounding controllers and needs to be managed in a coordinated way (see Figure 4.2)

A distributed control system for integrated electricity and natural gas systems was proposed in (Arnold et al., 2008b). A system consisting of several interconnected energy hubs was controlled by their respective control agents. In (Arnold et al., 2010) the study was extended to investigate a distributed MPC scheme and the dynamics of storage devices in natural gas systems.

Mean-variance portfolio theory and distributed control applied to a system of energy hubs interconnecting electricity and natural gas systems was investigated in (Arnold et al., 2008a).

4.2.3 Analysis of the potential to provide flexibility to the electrical power system

A framework to assess real-time demand response provision from the integration of energy systems was investigated in (Mancarella and Chicco, 2013b). The concept of 'electricity shifting potential' was introduced as an indicator of the possible reduction of electricity flowing from the external grid to the integrated energy system (without interrupting user's load). Demand response profitability maps were also introduced to visualize the benefits of electrical load shifting in the presence of incentives.

In (Kitapbayev et al., 2014, Kitapbayev et al., 2013) a method for the optimal control of thermal storage coupled to CHP units in the presence of uncertain market prices and the value of thermal storage as a demand response enabler was investigated.

The work on dynamic response provision in (Mancarella and Chicco, 2013b) was extended to analyse and quantify the benefits of providing ancillary services to the electricity network operator in (Mancarella and Chicco, 2013a). The concept of 'ancillary services profitability maps' were introduced to visualize how internal energy shifting potential in integrated energy systems can provide value through the provision of ancillary services.

4.2.4 Interdependency analysis

The operational interdependencies investigated in literature can be categorised as between the following energy systems,

- electricity and gas
- electricity and heat
- electricity, gas and heat

(a) Operational interdependencies between electricity and gas systems

Today, the interdependencies between electricity and gas systems are primarily due to the increasing number of gas fired power generation units (e.g. CCGT). The impact of natural gas prices on electricity generation scheduling and the impact of natural gas infrastructure constraints on the operation of electrical power systems were investigated in (Shahidehpour et al., 2005). The impact of wind variability on the GB gas and electricity supply was investigated in (Qadrdan et al., 2010) using a combined electricity and gas network OPF model. In (Qadrdan et al., 2014), novel operating strategies were recommended for the combined electricity and gas network in GB considering the uncertainty in wind power forecasts. Several studies have also investigated the impact of small scale gas fired power generation and electric vehicles on combined electric and gas distribution networks (Acha et al., 2010, Acha and Hernandez-Aramburo, 2008). Modelling of flexibility in the integrated electricity and gas network in the presence of large scale penetration of renewable energy and different heating supply scenarios was investigated in (Clegg et al., 2016)

Power to gas or the conversion of electricity to hydrogen (subsequently to synthetic methane if required) and using the gas infrastructure for the storage and transport of energy has gained significant interest in the recent years. A number of studies (Qadrdan et al., 2015, Clegg and Mancarella, 2015) have investigated the interdependencies introduced by power-to-gas units on the combined electricity and gas network operation in GB. The application of power-to-gas for seasonal storage in gas networks was investigated in (Clegg, 2016b).

(b) Operational interdependencies between electricity and heating systems

The interdependencies between electricity and heating systems primarily occur at district/community level and are due to

- combined production of electricity and heat in cogeneration systems
- use of thermal storage to increase CHP flexibility and ancillary services provision
- use of electric heating technologies (e.g. electric boilers) coupled with heating systems and thermal storage to provide demand response

The operation and planning of co-generation considering the interactions between electricity and heat systems has been investigated extensively (Salgado and Pedrero, 2008). The potential interactions between electricity and heating systems due to the provision of demand response have been examined in (Houwing et al., 2011, Arteconi et al., 2012). Comparison of different electricity and heat supply options for community energy schemes with operation and planning from techno-economic and local emissions perspectives was carried out in (Capuder et al., 2014).

(c) Interdependencies between electricity, gas and district heating systems

Combined heat and power units couple electricity, gas and district heating infrastructure. In (Liu and Mancarella, 2015), Sankey diagrams were used to illustrate the energy flows through the electricity, gas and district heating systems under several scenarios of CHP and heat pump penetration. The study also investigated the impact of different technologies on the steady state operational parameters of each network. The impact on district heating and natural gas grids when aiming towards electricity grid decarbonisation were investigated in (Kusch et al., 2012, Vandewalle et al., 2012a).

4.3 Energy performance assessment

The main approaches used in literature to assess the energy and environmental performance of integrated energy systems can be categorised as energy or exergy based. Energy performance indicators (e.g. energy efficiency, primary energy saving) are commonly used in the overall performance assessment of integrated energy systems (Mancarella, 2012). The performance is typically assessed compared to a benchmark system which, in most studies, is the separate production of each energy-carrier in reference production technologies.

Exergy performance indicators (e.g. exergetic efficiency, exergy destruction) which account for variations in the quality of different energy carriers have also been used for performance analysis in integrated energy systems (Krause et al., 2010, Bagdanavicius et al., 2012, Ramirez-Elizondo et al., 2013). An assessment of different community energy supply systems (CHP using natural gas or biomass gasification) using energy based and exergy based approaches was undertaken in

(Bagdanavicius et al., 2012). A comparison of using energy and exergy indicators in promoting cogeneration was investigated in (Nesheim and Ertesvåg, 2007) and the conflicts were highlighted. Exergy based approaches are widely used in thermal engineering research, however its application to real world engineering and power systems is limited.

A review of methods and performance criteria used to assess the energy and environmental performance of integrated energy systems was carried out in (Mancarella, 2013).

4.4 Design and expansion planning

The problem of the design and expansion planning of integrated energy systems is to identify the optimal combination of energy supply, conversion and storage technologies as well as the network infrastructure required to meet the estimated energy demand and its future evolution. Recent analyses argue that integrated design and expansion planning of multi-energy systems is beneficial compared to the independent development practiced today (Saldarriaga et al., 2013).

Literature on the design of integrated energy systems can be categorised as using deterministic or probabilistic methods of analyses.

(a) Deterministic models

Deterministic methods are used when variables that affect the investment are assumed to be known with a degree of certainty. Traditionally, the discounted cash flow method using NPV (net present value), IRR (internal rate of return) and payback time indicators are used to assess the profitability of an investment. The design of CHP coupled district heating systems using the NPV and IRR indicator for their economic assessment was investigated in (Horlock, 1987).

A method for expansion planning of an integrated electricity and gas system at the distribution level that has a high penetration of gas fired power generators was investigated in (Saldarriaga et al., 2013). The study claims lower investment costs compared to methods that consider expansion of each energy system independently. A method for the expansion planning of combined gas and electricity networks at the transmission level was investigated in (Chaudry et al., 2014). The model was used to analyse the GB gas and electricity system expansion for several scenarios of the low carbon transition.

The design of multi-energy supply infrastructure for new build schemes with carbon emissions constraints was investigated in (Rees et al., 2014). The objective of the study was to find the optimal mix of on-site and building level energy supply technologies that meets the energy service demand and targets of greenhouse gas emissions at a minimum cost to the developer.

A method for identifying the optimal coupling between networks in an integrated energy system that includes electricity, natural gas and district heating infrastructure was investigated in (Geidl and Andersson, 2006).

(b) Probabilistic models

Stochastic (or probabilistic) models are being used in design studies due to the uncertainties in the energy sector introduced by energy markets (e.g. natural gas price) and large volumes of intermittent generation. A method for computing probabilistic NPV and IRR indicators for cogeneration planning under uncertainty using Monte Carlo simulations was investigated in (Carpaneto et al., 2011a, Carpaneto et al., 2011b).

A method for valuing investments in multi-energy conversion, storage and demand side management under uncertainty was examined in (Kienzle and Andersson, 2011). The potential to provide demand side management to uncertain and volatile market prices was valued together with the efficiency gains of integrating energy systems. The study was extended for location dependent valuation of energy hubs with storage in (Kienzle and Andersson, 2010).

A method for assessing the optimal design of integrated energy systems considering their potential for providing response to forecasted marker prices was investigated in (Kitapbayev et al., 2013). The proposed approach uses real options valuation methods[12] as used in finance to capture long term uncertainties and investment flexibility (defer or accelerate investments). A method for infrastrcture expansion planning under uncertainty based on the real options theory can also be found in (Martinez-Cesena et al, 2015)

The mean-variance portfolio theory was used to investigate the different solutions for the design of integrated energy systems in (Favre-Perrod et al., 2010).

4.5 Reliability analysis

Assessing the reliability of the electrical power system is a mature field. However, limited work has been carried out investigating the reliability of other energy carrier systems (Helseth and Holen, 2006). A methodology for reliability analysis of the natural gas system based on the method used in electrical systems has been investigated in (Helseth and Holen, 2006). An assessment of the European natural gas system reliability was undertaken in (Olanrewaju et al., 2015).

The reliability analysis of combined electricity and natural gas systems has gained significant interest due to the increasing number of CCGTs in electrical power systems. Modelling of the natural gas system suitable for electrical power system reliability studies was proposed in (Munoz et al., 2003). A method for reliability analysis of the combined electricity and gas network was investigated in (Chaudry et al., 2013). A case study demonstrated the reliability analysis of GB's integrated gas and electricity network given uncertainty in wind variability, gas supply availability and outages to network assets.

A framework for reliability analysis in integrated energy systems, based on the energy hub modelling concept was developed in (Koeppel, 2007, Koeppel and Andersson, 2009). The model computes expected reliability of supply and Expected Energy Not Supplied (EENS). The model is used for systems with and without energy storage devices. The study claims that interconnections between different energy carriers are beneficial particularly for reducing expected energy not supplied in all energy carrier systems[13].

4.6 Modelling tools

A number of modelling tools are available to analyse different aspects of integrated energy systems. Reviews of the models and software tools available were under taken in several studies as outlined below,

---

[12] Real options theory captures the value from exercising the option, that is investing in the plant at a later stage and in a modular basis. Classical engineering economics assume the investment is carried out at the beginning of the analysis window, with no room for instance postponing the investment. On the other hand, in the presence of uncertainty there may be value in waiting.

[13] This is true for integrated electricity, natural gas and district heating systems as long as the ratings of the loads and installed components are similar [83]

- A review of modelling approaches and software tools available for the analyses of district-scale interactions in energy systems was undertaken in (Allegrini et al., 2015).
- A review of urban energy system models was carried out in (Keirstead et al., 2012). The models and tools were grouped according to their use in technology design, building design, urban climate, systems design and policy assessment.
- A review of a number of tools able to model multi-energy systems applicable to a city scale was undertaken in (Beuzekom et. al, 2015)
- A review of software tools available for analysing the integration of renewable energy into various energy systems was undertaken in (Connolly et al., 2010). The study reviewed 37 tools in collaboration with the tool developers or recommended points of contact.
- A review and survey of available tools for planning and analysis of community energy systems was undertaken in (Mendes et al., 2011).

An overview of some of the commonly used modelling tools collated from the review studies is shown in Table 4.2 (Mancarella, 2013).

Table 4.2: An overview of models and software tools used for integrated energy system analysis

	Analysis type					
	Network studies	**Operation**	**Design**	**Time Resolution/Horizon**	**Accessibility**	**Link**
EnergyPLAN	No	Yes	No	Hourly/Annual	Free	http://www.energyplan.eu/
RET Screen	No	No	Yes	Monthly/up to 50 years	Free	http://www.retscreen.net/
H2RES	No	Yes	No	Hourly/Annual	Internal research	http://h2res.fsb.hr/index.html
DER-CAM	No	Yes	Yes	Variable	Internal research and collaborations	https://building-microgrid.lbl.gov/projects/der-cam
eTransport	Yes	Yes	Yes	Hourly/Lifetime	Internal research	(Bakken et al., 2007)
SynCity	Yes	No	Yes	-	Internal research	(James Kierstead et al.)

5: Challenges and Research Gaps

Realisation of the potential benefits of integrating energy systems faces significant challenges. Some of the key challenges and research gaps are highlighted below.

5.1 Challenges

1. The fragmented institutional and market structures of different energy sectors

In the UK in particular, the energy supply systems, their markets and regulatory frameworks have traditionally been separated depending on the type of energy carrier. For example the markets and regulatory frameworks for electricity, natural gas and fuel oils are independent. The restructuring and privatisation of the energy supply businesses resulted in a fragmented institutional framework of individual energy systems where no single party was responsible for the seamless technical functioning and performance enhancement of the overall system. In a report by the IET (IET, 2014), the challenges faced by the electricity sector due to the multi-party institutional structure were highlighted. It is recognized that the effective decarbonisation of energy relies on a whole systems approach.

The existing detached institutional and market structure is a barrier to realising the benefits of integrating energy systems. The potential benefits need to be shared between multiple stakeholders that operate in independent markets. For example, the value of a CHP system is shared between the electricity and heat sector (low cost heat supply).

The success of integrated energy systems in Denmark (Meibom et al., 2013) and Sweden can in part be attributed to the role of municipal utilities that own and operate multiple energy carrier systems and are responsible for the entire local energy system.

2. The increased complexity of the overall energy system

Integration of multiple energy systems would result in a more complex energy system to manage and operate. The interdependencies between different energy systems and the ICT infrastructure that facilitates interoperability are complicated and require powerful models and software tools to analyse. It is argued that the integration of multiple energy systems can result in an energy supply system that is more susceptible to cascaded failures affecting reliability of supply.

3. Multidisciplinary nature of research and development in integrated energy systems

The integration of energy systems requires co-ordination and collaboration between traditionally detached stakeholders in the energy sector. Research and project development would be multi-disciplinary by nature and requires knowledge of the dissimilar technical, economic and market arrangements. It was mentioned at a HubNet workshop (minutes appended) that the lack of multi-disciplinary skills in the UK workforce is a challenge to progress in this area.

5.2 Research gaps

A number of research gaps in integrated energy systems research identified by a review of the literature and the stakeholder workshop are highlighted below.

1. Methods and tools for modelling and simulation of integrated energy systems need to be developed

Although there are an increasing number of studies investigating the integrated energy systems, the modelling and simulation of integrated energy systems is still an underdeveloped area of research. In particular studies should extend beyond single node and steady state energy flow regime to modelling dynamic behaviour of coupled energy networks and systems. Validation of models with actual data is required to build confidence in the simulations. This is essential for the design of integrated control algorithms and operation strategies to realise the benefits of synergies between networks.

2. Methods and software tools for integrated design, operation, expansion planning and reliability analysis need to be developed

There is a need for methods and tools to aid the co-ordinated design, operation and expansion planning of integrated energy systems. The models/tools need to consider interactions between different energy systems at different scales (community, district, regional, national, European) in sufficient detail. Otherwise there is a potential risk of conflicting results when the system boundary is altered.

3. Standard test networks to perform case studies and validate models are required

There is a need of standard test networks (similar to IEEE standard electricity networks) for natural gas, district heating and district cooling systems. The current practice is to develop case study networks or use data from an actual system for research purposes. This creates a challenge to compare and validate results from different research studies and hinders progress.

4. Assessment criteria for the quantification of interdependencies and the overall performance of the integrated energy system are required

The overall techno-economic performance and interdependencies between coupled energy systems need to be quantified. The independent energy systems have established their own performance assessment methods and evaluation criteria. There is a gap in literature of relevant indicators and assessment methods to characterize the overall performance and interdependencies between energy systems.

5. Quantitative evidence of the benefits of integrating energy systems needs to be demonstrated

There is a need to quantify the multi-party benefits (as discussed in Chapter 2) of co-ordinated design, operation and planning of the coupled energy system. Models and software tools will be required to analyse this complex energy system.

6. New opportunities for business innovation needs to be investigated

New business models that aggregate the multiple benefits of integrating energy systems need to be investigated. A comprehensive value proposition that can be realised within the current regulatory and market framework needs to be presented.

7. Demonstration projects are required to show evidence of the practical application and validation of research

Real projects that demonstrate the interoperability of integrated energy networks are required to validate the application of theoretical results.

8. Market design, policy drivers and regulation that promotes integration of energy systems needs to be investigated

There is a clear need for innovation in market design to promote co-ordination between multi-energy systems and realise the potential benefits. Similarly, policy instruments and regulation that can promote the realisation of benefits of energy system integration need to be investigated.

References

21ST CENTURY POWER PARTNERSHIP. 2014. *Flexibility in 21st century power systems* [Online]. Available: http://www.nrel.gov/docs/fy14osti/61721.pdf.

ABEYSEKERA, M. & WU, J. 2015. Method for Simultaneous Power Flow Analysis in Coupled Multi-vector Energy Networks. *Energy Procedia,* 75**,** 1165-1171.

ACHA, S., GREEN, T. C. & SHAH, N. Techno-economical tradeoffs from embedded technologies with storage capabilities on electric and gas distribution networks. Power and Energy Society General Meeting, 2010 IEEE, 25-29 July 2010 2010. 1-8.

ACHA, S. & HERNANDEZ-ARAMBURO, C. Integrated modelling of gas and electricity distribution networks with a high penetration of embedded generation. SmartGrids for Distribution, 2008. IET-CIRED. CIRED Seminar, 23-24 June 2008 2008. 1-4.

ALLEGRINI, J., OREHOUNIG, K., MAVROMATIDIS, G., RUESCH, F., DORER, V. & EVINS, R. 2015. A review of modelling approaches and tools for the simulation of district-scale energy systems. *Renewable and Sustainable Energy Reviews,* 52**,** 1391-1404.

ALMASSALKHI, M. & HISKENS, I. Impact of energy storage on cascade mitigation in multi-energy systems. 2012 IEEE Power and Energy Society General Meeting, 22-26 July 2012 2012. 1-8.

APPLIED ENERGY. 2015. *Special Issue on "Integrated Energy Systems"* [Online]. ELSEVIER. Available: http://www.journals.elsevier.com/applied-energy/call-for-papers/special-issue-on-integrated-energy-systems/.

ARNOLD, M., KIENZLE, F. & ANDERSSON, G. 2008a. Distributed Control Applied to Multi-Energy Generation Portfolios. *Smart Energy Strategis: Meeting the Climate Change Challenge.* Energy Science Center ETH Zurich.

ARNOLD, M., NEGENBORN, R. R., ANDERSSON, G. & DE SCHUTTER, B. Distributed control applied to combined electricity and natural gas infrastructures. Infrastructure Systems and Services: Building Networks for a Brighter Future (INFRA), 2008 First International Conference on, 10-12 Nov. 2008 2008b. 1-6.

ARNOLD, M., NEGENBORN, R. R., ANDERSSON, G. & DE SCHUTTER, B. Model-based predictive control applied to multi-carrier energy systems. Power & Energy Society General Meeting, 2009. PES '09. IEEE, 26-30 July 2009 2009. 1-8.

ARNOLD, M., NEGENBORN, R. R., ANDERSSON, G. & DE SCHUTTER, B. 2010. Distributed Predictive Control for Energy Hub Coordination in Coupled Electricity and Gas Networks. *In:* NEGENBORN, R. R., LUKSZO, Z. & HELLENDOORN, H. (eds.) *Intelligent Infrastructures.* Springer Netherlands.

ARTECONI, A., HEWITT, N. J. & POLONARA, F. 2012. State of the art of thermal storage for demand-side management. *Applied Energy,* 93**,** 371-389.

BAGDANAVICIUS, A., JENKINS, N. & HAMMOND, G. P. 2012. Assessment of community energy supply systems using energy, exergy and exergoeconomic analysis. *Energy,* 45**,** 247-255.

BAKKEN, B. H., SKJELBRED, H. I. & WOLFGANG, O. 2007. eTransport: Investment planning in energy supply systems with multiple energy carriers. *Energy,* 32**,** 1676-1689.

BRODECKI, L., TOMASCHEK, J., FAHL, U. & ALONSO, J. 2014. *Synergies in the integration of energy networks for electricity, gas, heating and cooling* [Online]. INSIGHT_E. Available: http://insightenergy.org/ckeditor_assets/attachments/37/rreb1.pdf [Accessed 1.

CAPUDER, T. & MANCARELLA, P. Modelling and assessment of the techno-economic and environmental performance of flexible Multi-Generation systems. Proceedings - 2014 Power Systems Computation Conference, PSCC 2014, 2014a.

CAPUDER, T. & MANCARELLA, P. 2014b. Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options. *Energy,* 71**,** 516-533.

CARDELL, J. B. Distributed resource participation in local balancing energy markets. 2007 IEEE POWERTECH Lausanne. 510-515.

CARPANETO, E., CHICCO, G., MANCARELLA, P. & RUSSO, A. 2011a. Cogeneration planning under uncertainty. Part I: Multiple time frame approach. *Applied Energy,* 88**,** 1059-1067.

CARPANETO, E., CHICCO, G., MANCARELLA, P. & RUSSO, A. 2011b. Cogeneration planning under uncertainty. Part II: Decision theory-based assessment of planning alternatives. *Applied Energy,* 88**,** 1075-1083.

CHAUDRY, M., JENKINS, N., QADRDAN, M. & WU, J. 2014. Combined gas and electricity network expansion planning. *Applied Energy,* 113**,** 1171-1187.

CHAUDRY, M., JENKINS, N. & STRBAC, G. 2008. Multi-time period combined gas and electricity network optimisation. *Electric Power Systems Research,* 78**,** 1265-1279.

CHAUDRY, M., WU, J. & JENKINS, N. 2013. A sequential Monte Carlo model of the combined GB gas and electricity network. *Energy Policy,* 62**,** 473-483.

CHICCO, G. & MANCARELLA, P. 2008a. Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part I: Models and indicators. *Energy,* 33**,** 410-417.

CHICCO, G. & MANCARELLA, P. 2008b. A unified model for energy and environmental performance assessment of natural gas-fueled poly-generation systems. *Energy Conversion and Management,* 49**,** 2069-2077.

CHICCO, G. & MANCARELLA, P. 2009. Matrix modelling of small-scale trigeneration systems and application to operational optimization. *Energy,* 34**,** 261-273.

CIPRIANI, G., DI DIO, V., GENDUSO, F., LA CASCIA, D., LIGA, R. & MICELI, R. 2013. Perspective on hydrogen energy carrier and its automotive applications. *International Journal of Hydrogen Energy*.

CLEGG, S. & MANCARELLA, P. Integrated electrical and gas network modelling for assessment of different power-and-heat options. Power Systems Computation Conference (PSCC), 2014, 18-22 Aug. 2014 2014. 1-7.

CLEGG, S. & MANCARELLA, P. 2015. Integrated Modeling and Assessment of the Operational Impact of Power-to-Gas (P2G) on Electrical and Gas Transmission Networks. *Sustainable Energy, IEEE Transactions on,* PP**,** 1-11.

CLEGG, S. & MANCARELLA, P. 2016. Storing renewables in the gas network: modelling of power-to-gas seasonal storage flexibility in low-carbon power systems. *IET Generation, Transmission & Distribution* [Online], 10. Available: http://digital-library.theiet.org/content/journals/10.1049/iet-gtd.2015.0439.

CONNOLLY, D., LUND, H., MATHIESEN, B. V. & LEAHY, M. 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy,* 87**,** 1059-1082.

DECC. 2012a. *Electricity System: Assessment of Future Challenges-Summary* [Online]. Available: https://www.gov.uk/government/publications/electricity-system-assessment-of-future-challenges.

DECC. 2012b. *The Future of Heating: A Strategic Framework for low carbon heat in the UK* [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48574/4805-future-heating-strategic-framework.pdf.

DECC. 2012c. *Gas Generation Strategy* [Online]. Available: http://www.decc.gov.uk/en/content/cms/meeting_energy/oil_gas/gasgenstrat/gasgenstrat.aspx

DECC. 2013. *The Future of Heating: Meeting the Challenge* [Online]. Available: https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge.

DECC. 2014a. *Community energy strategy* [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/275163/20140126Community_Energy_Strategy.pdf.

DECC. 2014b. *Digest of UK energy statistics (DUKES)* [Online]. Available: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes.

DECC. 2015. *Heat networks delivery funding* [Online]. UK Government. Available: https://www.gov.uk/government/publications/heat-networks-funding-stream-application-and-guidance-pack.

EERA. 2015. *Upcoming EERA JP Energy Systems Integration* [Online]. Available: http://www.eera-set.eu/eera-joint-programmes-jps/upcoming-eera-joint-programmes/upcoming-eera-jp-energy-systems-integration/.

ETI. 2014. *Smart Systems and Heat: Decarbonising heat for UK homes* [Online]. Available: http://www.eti.co.uk/wp-content/uploads/2015/03/Smart-Systems-and-Heat-Decarbonising-Heat-for-UK-Homes-.pdf.

ETI. 2015. *Energy Technologies Institute* [Online]. Available: http://www.eti.co.uk/.

EUROPEAN COMMISSION. 2015a. *Horizon 2020: Work Programme 2016-2017* [Online]. Available: http://ec.europa.eu/research/participants/data/ref/h2020/wp/2016_2017/main/h2020-wp1617-energy_en.pdf.

EUROPEAN COMMISSION. 2015b. *The Strategic Energy Technology Plan (SET) Plan* [Online]. Available: https://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan.

EUROPEAN POWER TO GAS. 2015. *Power to gas (demonstration) projects in Europe* [Online]. Available: http://www.europeanpowertogas.com/demonstrations.

FAVRE-PERROD, P., GEIDL, M., KLÖCKL, B. & KOEPPEL, G. 2005. A vision of future energy networks. *Power Engineering Society Inaugural Conference and Exposition in Africa, 2005 IEEE.*

FAVRE-PERROD, P., KIENZLE, F. & ANDERSSON, G. 2010. Modeling and design of future multi-energy generation and transmission systems. *European Transactions on Electrical Power,* 20**,** 994-1008.

FREDERIKSEN, S. & WERNER, S. 2013. *District heating and cooling,* Lund, Sweden, Studentlitteratur.

GAHLEITNER, G. 2013. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *International Journal of Hydrogen Energy,* 38**,** 2039-2061.

GEIDL, M. & ANDERSSON, G. 2006. Operational and structural optimization of multi-carrier energy systems. *European Transactions on Electrical Power,* 16**,** 463-477.

GEIDL, M. & ANDERSSON, G. 2007. Optimal Power Flow of Multiple Energy Carriers. *Power Systems, IEEE Transactions on,* 22**,** 145-155.

GEIDL, M. & ANDERSSON, G. 2008. Optimal power dispatch and conversion in systems with multiple energy carriers. Available: http://www.eeh.ee.ethz.ch/uploads/tx_ethpublications/pscc_2005_geidl.pdf.

GEIDL, M., G. KOEPPEL, P. FAVRE-PERROD, B. KLÖCKL, G. ANDERSSON, K. FRÖHLICH 2007. Energy hubs for the future. *IEEE Power & Energy Magazine.*

GOOD, N., MARTÍNEZ CESEÑA, E. A., ZHANG, L. & MANCARELLA, P. 2016. Techno-economic and business case assessment of low carbon technologies in distributed multi-energy systems. *Applied Energy,* 167**,** 158-172.

GROND, L., SCHULZE, P. & HOLSTEIN, J. 2013. *Systems analyses Power to Gas: A technology review* [Online]. Available: http://www.northseapowertogas.com/documents.

HEATON, C. 2014. *Modelling Low-carbon energy system designs with the ETI ESME Model* [Online]. Available: http://www.eti.co.uk/wp-content/uploads/2014/04/ESME_Modelling_Paper.pdf.

HELSETH, A. & HOLEN, A. T. Reliability modeling of gas and electric power distribution systems; similarities and differences. Probabilistic Methods Applied to Power Systems, 2006. PMAPS 2006. International Conference on, 11-15 June 2006 2006. 1-5.

HORLOCK, J. H. 1987. *Cogeneration-Combined Heat and Power (CHP);Thermodynamics and economics,* Great Britain, A. Wheaton & Co. Ltd., Exeter.
HOUWING, M., NEGENBORN, R. R. & DE SCHUTTER, B. 2011. Demand Response With Micro-CHP Systems. *Proceedings of the IEEE,* 99**,** 200-213.
HUBNET. 2015. *HubNet-A Hub for Energy Networks Research* [Online]. Available: http://www.hubnet.org.uk/.
HUGHES, N. & STRACHAN, N. 2010. Methodological review of UK and international low carbon scenarios. *Energy Policy,* 38**,** 6056-6065.
IEA. 2014. *Linking Heat and Electricity Systems* [Online]. Available: https://www.iea.org/publications/freepublications/publication/LinkingHeatandElectricitySystems.pdf.
IEEE 2013. Special Issue on Energy Systems Integration. *Power and Energy Magazine, ,* 5.
IET. 2014. *Britains Power System: The case for a system architect* [Online]. Available: http://www.theiet.org/factfiles/energy/brit-power-page.cfm.
IIESI. 2015a. *Educational Opportunities* [Online]. Available: http://iiesi.org/education.html.
IIESI. 2015b. *Summary of iiESI workshop on energy systems integration research challenges in London* [Online]. Available: http://iiesi.org/education.html.
INNOVATEUK. 2014. *Localised energy systems - a cross-sector approach* [Online]. Available: https://interact.innovateuk.org/-/localised-energy-systems-a-cross-sector-approach.
INNOVATEUK. 2015a. *Energy Systems Catapult* [Online]. Available: https://es.catapult.org.uk/.
INNOVATEUK. 2015b. *Integrated supply chains for energy systems* [Online]. Available: https://interact.innovateuk.org/-/integrated-supply-chains-for-energy-systems.
ITMPOWER 2013. Power-to-gas: A UK Feasibility study.
ITRC. 2015. *UK Infrastructure Transitions Research Consortium* [Online]. Available: http://www.itrc.org.uk/.
JAMES KIERSTEAD, NOURI SAMSATLI & NILAY SHAH. 2009. *SYNCITY: An integrated toolkit for urban energy systems modelling* [Online]. Available: http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1256566800920/6505269-1268260567624/Keirstead.pdf.
KEIRSTEAD, J., JENNINGS, M. & SIVAKUMAR, A. 2012. A review of urban energy system models: Approaches, challenges and opportunities. *Renewable and Sustainable Energy Reviews,* 16**,** 3847-3866.
KIENZLE, F. & ANDERSSON, G. Location-dependent valuation of energy hubs with storage in multi-carrier energy systems. 2010.
KIENZLE, F. & ANDERSSON, G. 2011. Valuing Investments in Multi-Energy Conversion, Storage, and Demand-Side Management Systems Under Uncertainty. *Sustainable Energy, IEEE Transactions on,* 2**,** 194-202.
KITAPBAYEV, Y., MORIARTY, J. & MANCARELLA, P. 2014. Stochastic control and real options valuation of thermal storage-enabled demand response from flexible district energy systems. *Applied Energy*.
KITAPBAYEV, Y., MORIARTY, J., MANCARELLA, P. & BLOCHLE, M. A real options assessment of operational flexibility in district energy systems. International Conference on the European Energy Market, EEM, 2013.
KOEPPEL, G. 2007. *Reliability considerations of future energy systems: multi-carrier systems and the effect of energy storage.* PhD, ETH Zurich.
KOEPPEL, G. & ANDERSSON, G. 2009. Reliability modeling of multi-carrier energy systems. *Energy,* 34**,** 235-244.
KRAUSE, T., KIENZLE, F., ART, S. & ANDERSSON, G. Maximizing exergy efficiency in multi-carrier energy systems. Power and Energy Society General Meeting, 2010 IEEE, 25-29 July 2010 2010. 1-8.
KROPOSKI, B., GARRETT, B., MACMILLAN, S., RICE, B., KOMOMUA, C., O'MALLEY, M. & ZIMMERLE, D. 2012. *Energy Systems Integration: A Convergence of Ideas* [Online]. NREL. Available: http://www.nrel.gov/docs/fy12osti/55649.pdf.

KUSCH, W., SCHMIDLA, T. & STADLER, I. 2012. Consequences for district heating and natural gas grids when aiming towards 100% electricity supply with renewables. *Energy,* 48**,** 153-159.
KYRIAKARAKOS, G., DOUNIS, A. I., ROZAKIS, S., ARVANITIS, K. G. & PAPADAKIS, G. 2011. Polygeneration microgrids: A viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel. *Applied Energy,* 88**,** 4517-4526.
KYRIAKARAKOS, G., PIROMALIS, D. D., DOUNIS, A. I., ARVANITIS, K. G. & PAPADAKIS, G. 2013. Intelligent demand side energy management system for autonomous polygeneration microgrids. *Applied Energy,* 103**,** 39-51.
LIU, C., SHAHIDEHPOUR, M. & WANG, J. 2011. Coordinated scheduling of electricity and natural gas infrastructures with a transient model for natural gas flow. *Chaos,* 21**,** 025102.
LIU, X. 2013. *Combined analysis of electricity and heat networks.* PhD thesis, Cardiff University.
LIU, X. & MANCARELLA, P. 2015. Modelling, assessment and Sankey diagrams of integrated electricity-heat-gas networks in multi-vector district energy systems. *Applied Energy*.
MANCARELLA, P. Distributed multi-generation options to increase environmental efficiency in smart cities. 2012.
MANCARELLA, P. 2013. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*.
MANCARELLA, P. & CHICCO, G. 2008. Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part II: Analysis techniques and application cases. *Energy,* 33**,** 418-430.
MANCARELLA, P. & CHICCO, G. Integrated energy and ancillary services provision in multi-energy systems. 2013a.
MANCARELLA, P. & CHICCO, G. 2013b. Real-Time Demand Response From Energy Shifting in Distributed Multi-Generation. *Smart Grid, IEEE Transactions on,* 4**,** 1928-1938.
MARTINEZ-MARES, A. & FUERTE-ESQUIVEL, C. R. 2012. A unified gas and power flow analysis in natural gas and electricity coupled networks. *IEEE Transactions on Power Systems,* 27**,** 2156-2166.
MARTINEZ CESENA, E. A., CAPUDER, T. & MANCARELLA, P. 2015. Flexible Distributed Multienergy Generation System Expansion Planning Under Uncertainty. *IEEE Transactions on Smart Grid*.
MEIBOM, P., HILGER, K. B., MADSEN, H. & VINTHER, D. 2013. Energy Comes Together in Denmark: The Key to a Future Fossil-Free Danish Power System. *Power and Energy Magazine, IEEE,* 11**,** 46-55.
MENDES, G., IOAKIMIDIS, C. & FERRÃO, P. 2011. On the planning and analysis of Integrated Community Energy Systems: A review and survey of available tools. *Renewable and Sustainable Energy Reviews,* 15**,** 4836-4854.
MUNOZ, J., JIMENEZ-REDONDO, N., PEREZ-RUIZ, J. & BARQUIN, J. Natural gas network modeling for power systems reliability studies. Power Tech Conference Proceedings, 2003 IEEE Bologna, 23-26 June 2003 2003. 8 pp. Vol.4.
NATIONALGRID. 2008. *Gas Transportation Transmission Planning Code* [Online]. Available: http://www.nationalgrid.com/NR/rdonlyres/4E9A7154-E991-4A51-8219-105817A8E1E3/30742/200810TPCApprovedv10.pdf.
NATIONALGRID. 2013. *UK Future Energy Scenarios* [Online]. Nationalgrid. Available: http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/FES/Documents-archive/.
NESHEIM, S. J. & ERTESVÅG, I. S. 2007. Efficiencies and indicators defined to promote combined heat and power. *Energy Conversion and Management,* 48**,** 1004-1015.
NIEMI, R., MIKKOLA, J. & LUND, P. D. 2012. Urban energy systems with smart multi-carrier energy networks and renewable energy generation. *Renewable Energy,* 48**,** 524-536.
NREL. 2015a. *Energy Systems Integration* [Online]. Available: http://www.nrel.gov/esi/.
NREL. 2015b. *Energy Systems Integration Facility* [Online]. Available: http://www.nrel.gov/esif/.
OFGEM. 2015. *Network Innovation* [Online]. Available: https://www.ofgem.gov.uk/network-regulation-riio-model/network-innovation.

OLANREWAJU, O. T., CHAUDRY, M., QADRDAN, M., WU, J. & JENKINS, N. 2015. Vulnerability assessment of the European natural gas supply. *Proceedings of the Institution of Civil Engineers - Energy,* 168**,** 5-15.

PATEL, S. 2012. Progress for Germany's power-to-gas drive. *Power,* 156.

PEARSON, P., WATSON J. 2012. *UK Energy Policy 1980-2010: A history and lessons to be learnt* [Online]. Available: http://www.theiet.org/factfiles/energy/uk-energy-policy-page.cfm.

PYE, S., SABIO, N. & STRACHAN, N. 2015. An integrated systematic analysis of uncertainties in UK energy transition pathways. *Energy Policy,* 87**,** 673-684.

QADRDAN, M., ABEYSEKERA, M., CHAUDRY, M., WU, J. & JENKINS, N. 2015. Role of power-to-gas in an integrated gas and electricity system in Great Britain. *International Journal of Hydrogen Energy,* 40**,** 5763-5775.

QADRDAN, M., CHAUDRY, M., WU, J., JENKINS, N. & EKANAYAKE, J. 2010. Impact of a large penetration of wind generation on the GB gas network. *Energy Policy,* 38**,** 5684-5695.

QADRDAN, M., CHAUDRY, M., WU, J., JENKINS, N. & EKANAYAKE, J. 2013. Impact of a large penetration of wind generation on the GB gas network. *Energy Policy,* 38**,** 5684-5695.

QADRDAN, M., WU, J., JENKINS, N. & EKANAYAKE, J. 2014. Operating strategies for a gb integrated gas and electricity network considering the uncertainty in wind power forecasts. *IEEE Transactions on Sustainable Energy,* 5**,** 128-138.

RAMIREZ-ELIZONDO, L., VELEZ, V. & PAAP, G. C. A technique for unit commitment in multiple energy carrier systems with storage. Environment and Electrical Engineering (EEEIC), 2010 9th International Conference on, 16-19 May 2010 2010. 106-109.

RAMIREZ-ELIZONDO, L. M. & PAAP, G. C. Unit commitment in multiple energy carrier systems. North American Power Symposium (NAPS), 2009, 4-6 Oct. 2009 2009. 1-6.

RAMÍREZ-ELIZONDO, L. M. & PAAP, G. C. 2015. Scheduling and control framework for distribution-level systems containing multiple energy carrier systems: Theoretical approach and illustrative example. *International Journal of Electrical Power & Energy Systems,* 66**,** 194-215.

RAMIREZ-ELIZONDO, L. M., PAAP, G. C., AMMERLAAN, R., NEGENBORN, R. R. & TOONSSEN, R. 2013. On the energy, exergy and cost optimisation of multi-energy-carrier power systems. *International Journal of Exergy,* 13**,** 364-386.

RASTETTER, R. W.-G. A. 2013. Power to Gas: The Final Breakthrough for the Hydrogen Economy? *Green,* Volume 3**,** Pages 69–78.

REES, M. T., WU, J., JENKINS, N. & ABEYSEKERA, M. 2014. Carbon constrained design of energy infrastructure for new build schemes. *Applied Energy,* 113**,** 1220-1234.

REZAIE, B. & ROSEN, M. A. 2012. District heating and cooling: Review of technology and potential enhancements. *Applied Energy,* 93**,** 2-10.

RINALDI, S. M., PEERENBOOM, J. P. & KELLY, T. K. 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. *Control Systems, IEEE,* 21**,** 11-25.

RTP ENGINE ROOM. 2015. *Distributing Power: A transition to a civic energy future* [Online]. Available: http://www.realisingtransitionpathways.org.uk/realisingtransitionpathways/news/distributing_power.html.

RUTTER, P. & KEIRSTEAD, J. 2012. A brief history and the possible future of urban energy systems. *Energy Policy,* 50**,** 72-80.

SALDARRIAGA, C. A., HINCAPIÉ, R. A. & SALAZAR, H. 2013. A holistic approach for planning natural gas and electricity distribution networks. *IEEE Transactions on Power Systems,* 28**,** 4052-4063.

SALGADO, F. & PEDRERO, P. 2008. Short-term operation planning on cogeneration systems: A survey. *Electric Power Systems Research,* 78**,** 835-848.

SEUNGWON, A., QING, L. & GEDRA, T. W. Natural gas and electricity optimal power flow. Transmission and Distribution Conference and Exposition, 2003 IEEE PES, 7-12 Sept. 2003 2003. 138-143 Vol.1.

SHAHIDEHPOUR, M., FU, Y. & WIEDMAN, T. 2005. Impact of Natural Gas Infrastructure on Electric Power Systems. *Proceedings of the IEEE,* 93**,** 1042-1056.

STRBAC, G., AUNEDI, M. & AL., P. D. E. 2012. *Strategic assessment of the role and value of energy storage systems in the UK low carbon energy future* [Online]. Report for Carbon Trust: Energy futures lab, Imperial college London. Available: https://www.carbontrust.com/media/129310/energy-storage-systems-role-value-strategic-assessment.pdf.

UKERC. 2014a. *Energy Strategy Under Uncertainty* [Online]. Available: http://www.ukerc.ac.uk/support/Energy+Strategy+Under+Uncertainty+External.

UKERC. 2014b. *Energy Supply Theme* [Online]. Available: http://www.ukerc.ac.uk/programmes/energy-supply.html.

VANDEWALLE, J., KEYAERTS, N. & D'HAESELEER, W. The role of thermal storage and natural gas in a smart energy system. 2012a.

VANDEWALLE, J., KEYAERTS, N. & D'HAESELEER, W. The role of thermal storage and natural gas in a smart energy system. European Energy Market (EEM), 2012 9th International Conference on the, 10-12 May 2012 2012b. 1-9.

VELEZ, V., RAMIREZ-ELIZONDO, L. & PAAP, G. C. Control strategy for an autonomous energy system with electricity and heat flows. Intelligent System Application to Power Systems (ISAP), 2011 16th International Conference on, 25-28 Sept. 2011 2011. 1-6.

VOORSPOOLS, K. R. & HAESELEER, W. D. D. 2003. The impact of the implementation of cogeneration in a given energetic context. *IEEE Transactions on Energy Conversion,* 18**,** 135-141.

WHOLESEM. 2015. *Whole Systems Energy Modelling Consortium* [Online]. Available: http://www.wholesem.ac.uk/.

WOOD, A. J. & WOLLENBERG, B. F. 1984. *Power Generation, Operation and Control*, John Wiley & Sons, Inc.

XU, X., HONGJIE, J., CHIANG, H. D., YU, D. C. & WANG, D. 2015a. Dynamic Modeling and Interaction of Hybrid Natural Gas and Electricity Supply System in Microgrid. *Power Systems, IEEE Transactions on,* 30**,** 1212-1221.

XU, X., JIA, H., WANG, D., YU, D. C. & CHIANG, H.-D. 2015b. Hierarchical energy management system for multi-source multi-product microgrids. *Renewable Energy,* 78**,** 621-630.

XU, X., JIN, X., JIA, H., YU, X. & LI, K. 2015c. Hierarchical management for integrated community energy systems. *Applied Energy,* 160**,** 231-243.

Appendix I

Table I: EPSRC funded research programmes investigating integration of energy systems

	Project Title	Lead Organization	Start	End	Grant value[14]	Energy Vectors			
						Elec	Gas	Thermal	Hydrogen
1	PLATFORM: Decentralized polygeneration of energy	University of Surrey	Nov 05	Aug 10	£710,606	√	√	√	
2	Centre for Integrated Renewable Energy Generation and Supply	Cardiff University	Jan 08	Dec12	£1,512,962	√	√	√	√
3	SUPERGEN FLEXNET	University of Strathclyde	Oct07	Mar12	£6,876,795	√	√	√	
4	SUPERGEN HDPS, HiDEF (Highly decentralized energy futures)	University of Strathclyde	Oct09	Sept12	£4,177,322	√	√	√	
5	HubNET: Research leadership and networking for energy networks	Imperial College	Jan11	Dec15	£4,723,735	√	√	√	√
6	Grand challenge Top and Tail	Imperial College	May11	Apr15	£4,108,875	√	√	√	
7	Multi-Vector Energy Distribution System Modelling and Optimisation with Integrated Demand Side Response	University of Bath	Sep 14	Aug 17	£241,601	√	√		
8	ITRC: Infrastructure transitions research consortium-Long term dynamics	University of Oxford	Feb11	Jan16	£4,780,610	√	√		
9	WholeSEM: Whole systems energy modelling consortium	UCL	Jul13	Jul17	£4,607,765	√	√	√	√
10	UKERC	Imperial College	May14	Apr19	£13,531,962	√	√	√	√
11	Adaptation and resilience in energy systems (ARIES)	University of Edinburgh	Nov11	Oct15	£771,708	√	√		
12	Adaptation and resilience in energy systems (ARIES)	Heriot Watt University	Feb12	Oct15	£388,079	√	√		
13	Hydrogen's value in the energy system (HYVE)	UCL	Jun 14	May17	£700,396	√	√		√
14	MY-STORE : Multi-energy storage-Social, techno-economic, regulatory	University of Manchester	Oct 15	Mar19	£1,268,170	√	√	√	√

[14] refers to the total grant value and not the amount specifically awarded to integrated energy systems research

Appendix II

Minutes of Workshop on Multi-Vector Energy Systems

Room 611, Electronic and Electrical Engineering Department
Imperial College London
10:00 – 15:00 hrs, Friday 31st October 2014

1. The workshop presentations and discussions were organized under the following topics.
   a) The current state of multi-vector energy systems in UK and Europe.
      - Presentation by Prof. J Yan on the research landscape in multi-energy network integration/Future energy transitions (Slides attached)
      - Presentation by DELTA EE on the heat decarbonising pathways for the UK (Slides attached)

   b) Identify current research and future research needs
      - Presentation by Dr. Thilo Kruse on the project “Vision of Future Energy Networks” and the Energy hub concept (Slides attached)

   c) Identify arguments for an integrated approach to energy supply
      - Presentation by John Marsh on the Kings Cross development (Slides attached)

   d) What are the benefits and costs of multi-vector energy systems?

What is a multi-vector energy system (MES)?

2. The different views on the definitions of ‘multi-vector energy system’ were discussed. Following are the views expressed,
   a) When one energy-vector system interacts with another
   b) When competition exists between energy vectors to meet the same energy service
   c) When one energy-vector relies on other energy vectors
3. The difficulty in setting a boundary for MES due to interactions between scales (building, city etc.) was discussed. MES concepts can be applied to a domestic dwelling as well as to national level energy balance. The choice of system boundary needs to be considered carefully to capture interactions between scales in sufficient detail.
4. The three dimensionality in the problem of whole energy system modeling i.e. the space, time and human dimensions should be considered. The geographical nature of the multi-vector energy system problem should also be considered.
5. The argument for energy network integration need to be set out more convincingly backed by quantitative evidence.

What are the challenges?

6. Evidence on future energy scenarios show that all energy networks will play an essential role in achieving the 2050 emissions target.
7. The challenges in realizing co-ordinated design and operation of multi-energy networks were discussed. Following are the views expressed.
   a) Complexity that arises from the integration of different energy carrier networks
   b) Difficulty in optimizing at different levels in the energy system i.e systems, subsystems and components
   c) The interactions and interdependencies among systems and the environment
   d) Uncertainty in the robustness of an integrated system
   e) Uncertainty whether the system and services are implementable
   f) Harmonising the way/time scales different energy markets work is a challenge (Gas on a daily basis while electricity networks markets balanced half hourly)

8. The existing fragmented market structure was discussed as a significant barrier to realise the benefits of integrated design and planning of MES. The un-regulated market for heat was also seen as a barrier. However, there is a belief that this particular issue will be resolved soon.
9. The challenge to set up collaboration between stakeholders operating in dissimilar markets was seen as a significant barrier.
10. The challenges of convincing multi party benefits of energy network integration were discussed.
11. The lack of multi-disciplinary skills in the UK workforce was discussed as a challenge moving forward.
12. It remains a challenge to realise the economies of scale that would be possible from multi-energy networks integration.
13. The predominant market penetration of natural gas boilers was seen as a major challenge.

What are the drivers for energy networks integration?

Regulation

14. Regulation was mentioned as a main driver in the Kings Cross case study to consider a CHP coupled district heating system. The following were discussed
    - There was a regulatory requirement to achieve a 50% reduction in emissions in energy supply across the development and the use of a CHP driven district heating system was considered the best option.
    - It was also mentioned that without regulatory requirements stated in the 'London Plan', the developer would not have considered district heating as a possible energy solution.
    - Contractual agreements obligate all buildings in the development area to connect to the DH network.
    - Another driver was the requirement that all new homes have to be zero carbon by 2016.
15. Ofgem is considering regulation on heat utility businesses in the near future.

Market drivers

16. Heat is increasingly seen as a new utility business.
17. The opportunity to own all energy infrastructure on site and make money on the use of the system was seen as driver in the Kings Cross case (By forming an ESCo)
18. Future energy scenario modelling suggests that 20% of all residential heat demand will be supplied by heat networks by 2050.
19. There is also a big opportunity for hybrid heat pumps and micro CHP to enter the UK domestic market as a transitional technology from the gas boiler.
20. Denmark is focused on a significant growth in heat pumps both at a domestic and network level due to the high wind energy penetration in the country.
21. Insight into the evolution of Europe's heating and gas markets gives clear driver for energy networks integration.
22. Innovative financing models will create new markets for energy network integration.

Techno-economic drivers

23. There is a clear opportunity in the new built sector to provide an integrated multi-vector energy system.
24. There is a driver to future proof the energy supply systems from the uncertainties in power/heat generation technology uptake going in to the future. In the Kings Cross case it was mentioned as the grid electricity decarbonises (emissions saving from CHP drops), they would consider replacing the current gas fired CHP engines with biomass CHP units.
25. There are opportunities for design and operational optimisation by a system owned and operated by a single commercial entity.
26. The challenge of a heat electrification only scenario was seen as another driver for heat network uptake and the subsequent coupling of networks (40GW of additional generation capacity required)
27. Economies of scale
28. Diminishing technology costs were seen as an economic driver.
29. A classic problem of not having an integrated approach was evident in the Swedish and Denmark case where zero marginal cost electricity was due to high CHP and Nuclear/Coal mix.

What are the anticipated benefits?

30. The recent interest in energy network integration and smart management of distributed local energy systems is due to the need to support balancing of the electricity network at the transmission level.

31. The flexibility offered by an integrated multi-vector energy system will be valued when a large amount of intermittent renewable power is utilized.
32. The main benefits of energy networks integration were discussed as
    a) Possibility to reduce primary fuel consumption and thereby reduce carbon emissions
    b) Economies of scale
    c) Enhanced energy storage capabilities
    d) Cost reductions in operation (This has not yet been quantified)
    e) Future proofing network infrastructure for technology advances by leaving room for fuel flexibility
    f) Possibility for spatial and temporal optimization of fuel use
33. In addition, the Kings Cross case study showed clear benefits in construction costs where design and construction of the system was done by a single party. There were clear cost reductions in both capital and maintenance expenditure due to single excavations for electricity cables, gas, water and heat pipelines and fibre optic cables.
34. Opportunities for new market and business models were also discussed as a potential benefit.

<u>Current and previous research</u>

35. Prof. J Yan's presented multiple projects on multi-energy vectors (demonstration and research) initiated under the 'Future energy' programme (Slides attached).
36. Thilo Krause presented the project 'Vision of future energy networks' and the 'Energy hubs' concept developed within the project
    - Sponsors of the project were – Swiss Federal Office of Energy, AREVA, ABB, Siements,Swiss Institute
    - The motivation for the project was to optimise the energy supply chain from production over transmission/distribution to final consumption of multi-energy carriers
    - Both current and future technologies were modelled
    - The development of the so-called energy hub was to create the interface between energy producers, consumers and the transportation infrastructure
    - The motivation of the project was to model complex interactions between different energy carriers and coupling technologies and exploit synergies between them to meet the final demand
    - The following was accomplished
        - Sound mathematical foundation of energy hubs
        - Multi-energy carrier optimal power flow
        - Reliability assessment of multi-energy carrier networks
        - Risk assessment and investment strategies in multi-energy carrier networks
        - Energy hubs – system dynamics and control (model predictive control – project with Zurich-EV)
        - Integration of plug-in hybrid vehicles to the energy hub modelling framework
    - Energy hubs was presented as a scalable and versatile modelling approach for multi-vector energy system research
    - Several case studies of national, European level and a plug-in hybrid vehicle was presented
37. Several European projects researching multi-vector energy system were mentioned
    - Epi-CUP/Ideas for cities/Ten-E and Power nodes concepts
38. Denmark and Germany's interest in converting excess electricity to hydrogen and storing in the gas infrastructure was discussed.

<u>Understanding complexities in the research area</u>

39. General feeling of the complexity of analysing interactions and interdependencies between different energy-vector networks was resounding.
40. Thilo Krause mentioned the optimization problem was very complex and had to use additional measures to find starting values for the numerical model. In some occasions 'Particle swarm optimization' was used.
41. Validation of the simulations were considered an important part of the research work done.
42. It was discussed whether the problems can be generalised, or whether its location specific by nature.
    - Thilo Krause mentioned this was the main barrier to commercialize a software developed on the energy hubs concept.
43. The question was raised to what extent uncertainties were considered in the Energy Hub model. It was mentioned due to the large dimensionality of the problem, studies were deterministic even though several other research have carried out Monte Carlo simulations.

44. The question of the time constant differences in balancing networks were not studied in detail in any research discussed.
    - Energy storage was considered in some studies, however the time scales of balancing were the same.
45. Big data was mentioned as a concern on increasing complexity, however was argued to be a different problem to the one being considered.
46. The complexity of understanding and combining different physics between interacting systems was discussed.
47. The problem of how to find a good balance in granularity of time and spacial representation of different systems was mentioned.
48. Co-ordination of research activities between different stakeholders is crucial but is a difficult challenge. -This might require a policy change on how energy networks are managed and operated.
49. There are trade-offs between computational complexity of models and level of detail (number of energy vectors) in the problem considered. However, this depends on the research question to be answered.

Research and modelling needs

50. Modelling of integrated energy systems is required when the interactions between energy-vectors become significant e.g. electricity and gas in the UK wind case.
51. Time scales for modelling are an important area to be considered due to different time scales in balancing different networks.
52. Energy storage is a key area to consider when integrating multi-energy networks.
    - The main advantage of flexibility comes from the possibility for energy storage.
53. Modelling tools need to consider interactions between energy vectors at different scales (building level, city, national) in the energy system. Otherwise there is a risk of converging in suboptimal solutions. Looking at options at a single scale/system needs to be complemented with studies at other levels.
54. There are no tools available that take into account market behaviour. This will be an important feature moving forward.
55. There is a very clear need for generic networks (similar to IEEE standards) to be developed for analysis/research to be carried out.
56. Whole supply-chain research needs to be developed.
    - Other sectors such as water and transport can also be included.
57. A clear distinction between the new built sector and the retrofit sector needs to be made when conclusions are drawn.
58. Therefore not a single but a set of modelling tools will be required.
59. There is certainly an argument to be made to consider electricity, gas and heat in the IET whole electricity systems initiative.
60. It is important to understand who will be interested in this research. Therefore, it is important to identify international research programmes and industrial initiatives (manufacturers/technology developers).
61. Economies of scale needs to be shown.
62. Innovative business models/cases need to be shown.

Where are the research opportunities?

63. Energy storage, ESCo's and community energy systems are current topics in the European energy research landscape.
64. Community energy systems and ESCo's were discussed as an ideal test bed to trial integrated design and co-ordinated operation of multi-vector energy networks.
65. It was argued that ESCo's and community energy programmes are more of a social and commercial problem rather than a technical issue.

Other discussion points

66. The multi-disciplinary nature of the area is a big challenge due to the lack of skilled professionals.
67. A role titled energy engineer can be intended for the future.

Attendees:

	Name	Institution
1	Prof. J Yan	KTH Stockholm
2	Dr. Thilo Krause	ETH Zurich
3	Prof. Goran Strabac	Imperial College
4	Prof. Gareth Harrison	University of Edinburgh
5	Mr. Nick Smailes	Innovate UK
6	Mr. Liam Lidstone	ETI
7	Mr. Dave Wagstaff	National Grid
8	Dr. Perluigi Mancerella	University of Manchester
9	Prof. Nick Jenkins	Cardiff University
10	Dr. Jianzhong Wu	
11	Dr. Modassar Chaudry	
12	Mr. Muditha Abeysekera	
13	Dr. Meysam Qadrdan	Imperial College
14	Mr. John Marsh	GTC
15	Mr. Aravin Vythilingam	
16	Mr. Stephen Harkin	Delta EE
17	Ms. Jennifer Woodruff	WPD
18	Ms. Olivia Carpenter	PPA Energy
19	Prof. Tim Green	Imperial College
20	Dr. Mahesh Sooriyabandara	Toshiba TRL
21	Dr Nouri Samsatli	Imperial College
22	Prof. Furong Li	University of Bath
23	Dr Marko Aunedi	Imperial College
24	Mr. Hossein Ameli	Imperial College