UKERC Energy Supply Theme

Synthesis Report

Working Paper

August 2014

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Abbreviations

BIGGT – Biomass Integrated Gasification Gas Turbine

BIGCC – Biomass Integrated Gasification Combined Cycle

BST – Biomass Steam Turbine

CCGT – Combined Cycle Gas Turbine

CCS – Carbon Capture and Storage

CGEN – Combined Gas and Electricity Network model

CHP – Combined Heat and Power

COP – Coefficient of Performance

DHN – District Heating Networks

DHW – Domestic Hot Water System

DES – District Energy Systems

DECC – Department of Energy and Climate Change

EMR – Electricity Market Reform

EU ETS – European Union Emissions Trading System

GT – Gas Turbine

ICE – Internal Combustion Engine

IPCC – Intergovernmental Panel on Climate Change

LNG – Liquefied Natural Gas

NETSO – National Electricity Transmission System Operator

OCGT – Open Cycle Gas Turbine

ORC – Organic Rankine Cycle

UKERC – the UK Energy Research Centre

1. Introduction

Climate change is one of the greatest threats facing the world today. In its latest assessment report the IPCC (*Climate Change 2013)* stated that "it is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations" (IPCC, 2013).

The UK is committed to reduce greenhouse gas emissions. This was illustrated by adoption of the Climate Change Act in 2008 which legally binds the UK to reduce carbon emissions by 80% (from 1990 levels) by 2050. To ensure that the obligations stipulated in the Act will be achieved, the Carbon Plan was published in June 2011 (DECC, 2012a). A commitment to halve greenhouse emissions, based on 1990 levels, by the mid-2020s was set out and four interim five-yearly carbon budgets for the period from 2008 to 2027 were defined. The Carbon Plan identified three challenges: climate change, energy security, and recognition that the transition to a low carbon economy must be performed in a way that minimises costs and maximises benefits to the economy.

The Carbon Plan identifies six sectors which must be transformed to achieve the proposed carbon budget targets; low carbon buildings, low carbon transport, low carbon industry, low carbon electricity, "agriculture, land use and forestry" and "waste resource and resource efficiency". The sectors, their associated 2009 proportion of carbon emissions and the proposed measures under the Carbon Plan are shown in Table 1.

The Carbon Plan envisages that the decarbonisation of heating and cooling supply will take place at both building and network level. The aim is that natural gas combustion in individual buildings will be phased out by 2050 to meet the UK's emission targets (DECC, 2012b). Presently, energy for heating and cooling is supplied mainly through the gas and electricity networks, and using oil (Figure 1). The decarbonisation of heating and cooling supplies is most likely to involve transition from gas and oil boilers to low carbon heating alternatives, such as heat pumps, micro Combined Heat and Power (CHP) or biomass boilers. In addition, the government aims "to see the micro-generation sector move into the energy mainstream, offering consumers affordable, and cost-effective low carbon energy products" (DECC, 2011a).

Table 1: Carbon Plan – Energy use sectors and planned actions

Area	Approximate Proportion of UK Annual Carbon Emissions, by end use and by source (DECC, 2012a).	Planned Actions
Buildings	By end use: 38% By source: 17%	Improvement of insulation. Improvement of heating controls. Smart metering. More efficient use of hot water. Decarbonisation of electricity and gas supply.
Transport	By end use: 24% By source: 22%	Transition to Ultra Low Emission Vehicles (ULEV) by 2050 (batteries, hydrogen fuel cells, biofuels or a mix). Electrification of rail. More efficient driving techniques.
Industry	By end use: 23% By source: 23%	Process optimisation. Heat recovery. Fuel switching. Carbon Capture and Storage (CCS). Recycling and remelting.
Electricity Generation	By end use: 0% By source: 27%	Increase in Renewables. Increase in Nuclear. Fossil fuels with CCS. Electricity Market Reform.
Agriculture and Forestry	By end use: 9% By source: 9%	Marine and land based energy production/carbon emission mitigation.
Waste	By end use: 3% By source: 3%	Waste reduction. Reduction of landfill methane. Energy recovery from residual waste.

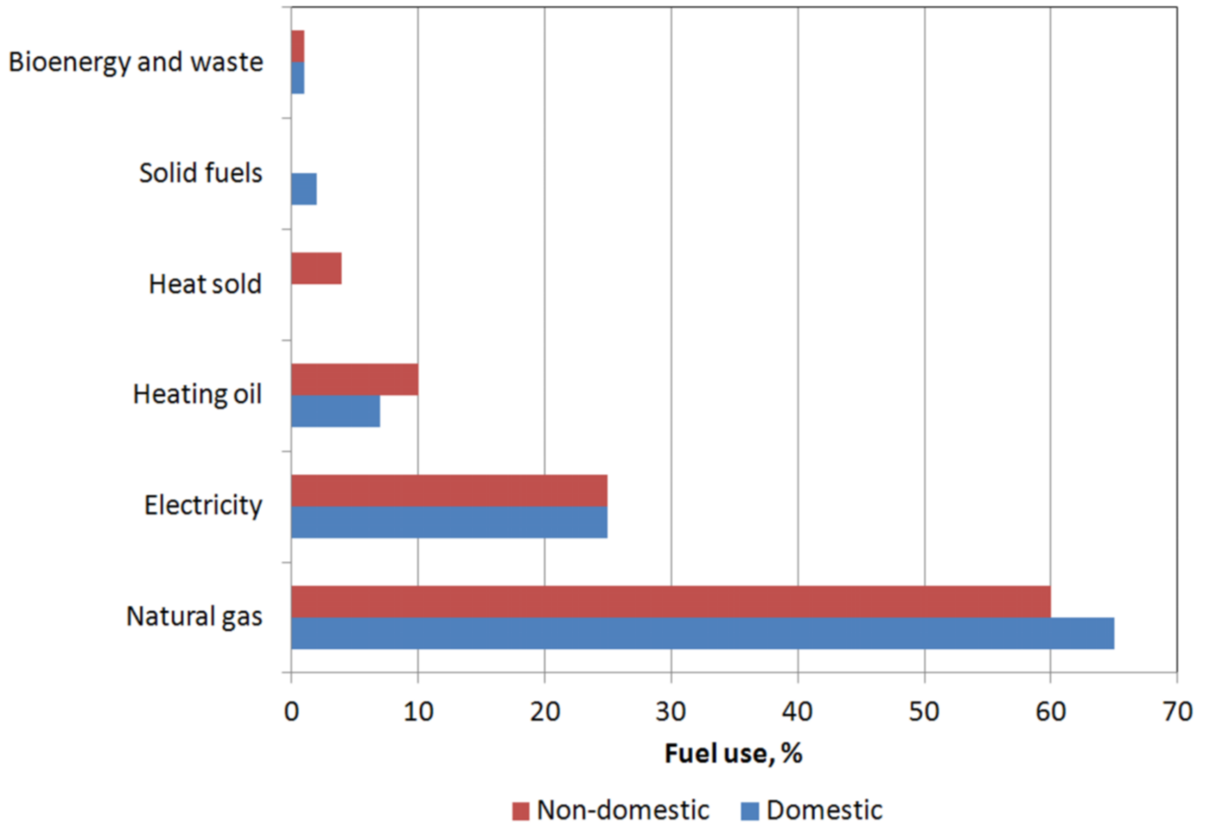


Figure 1: Final fuel use in domestic and non-domestic buildings 2011 (DECC, 2013)

At the network level, established technologies can contribute to the decarbonisation of heat. These include:

- CHP technologies with Heat Networks. CHP can use a range of fuels including biomass, waste and bioliquids as well as fossil fuels. At present CHP is most commonly used by industry to provide heat and electricity for large sites (e.g. hospitals). However, it can also be used for supplying heat to smaller buildings through heat networks.

- Gas grid biomethane and/or hydrogen injection technologies. Biomass and waste can be converted to gas and upgraded to biomethane, which can replace or blend with natural gas. Biomethane is compatible with existing boilers and can be directly injected into the gas network. Hydrogen can be produced from hydrocarbons, such as natural gas, biomass and coal or from electrolysis of water using electricity from low carbon sources (Axon *et al.*, 2012). Hydrogen injection could be achieved using one of three options: direct injection of hydrogen in very low concentrations; complete replacement of natural gas, or by combining hydrogen with carbon dioxide and producing synthetic methane for direct injection into the gas grid (DECC, 2013).

Energy use in buildings has been investigated by the UKERC Energy Demand theme (Janda, 2011; Bergman *et al.*, 2011; Hamilton *et al.*, 2012). Low carbon heat supply for buildings at individual and network level was studied by the UKERC Energy Supply theme. A review of the research conducted is presented in chapter 1 of this report.

Since 1990, carbon emissions in the electricity generation sector have fallen by 23% and carbon intensity has reduced from 690 to 448 gCO_2/kWh. It is planned that, by 2050, the electricity generation sector will be substantially decarbonised. Due to the increased energy demand, electricity supply may need to increase by 30–60% by 2050.

Various energy scenarios suggest that around 40–70 GW of new low carbon electricity generating capacity will be needed by 2030. It is expected that nuclear, renewable energy sources and fossil fuels with CCS will need to be deployed to achieve carbon emission targets. Additionally, increased flexibility in the balancing of demand and supply will be required due, in part, to the anticipated higher share of intermittent renewable energy sources.

Six key areas that will enable the low carbon transition were identified in the Carbon Plan: Electricity Market Reform (EMR), actions to facilitate nuclear energy, CCS, renewable sources, unabated gas fired plant for system balancing and investment in the electricity system. The Electricity Market Reform has been designed to address problems faced by low carbon generators such as insufficient investment in low carbon generators, poor market liquidity and regulatory burdens.

A number of UKERC projects have analysed technological, economic and policy issues related to EMR, CCS potential and global gas security including a TPA (Technology and Policy Assessment theme) report on power generation cost methodologies (Gross *et al.*, 2013), and Research Fund projects on uncertainties relating to the development and deployment of CCS (Watson *et al.*, 2012) and the geopolitics of global gas security (Bradshaw *et al.* 2013). Within the Energy Supply theme, UKERC research has focused on electricity market design issues (Baker *et al.*, 2009; 2010; 2011).

The Carbon Plan recognised that efficiency has to increase in all sectors and that oil and gas used for transport, heating and the power industry needs to be replaced by electricity, sustainable bioenergy or hydrogen. The importance of energy efficiency was reflected in the Energy Efficiency Strategy (DECC, 2012), published a year after the Carbon Plan. It was estimated that, through cost effective investment in energy efficiency, 196 TWh could be saved by 2020. The Strategy identified four groups of barriers to greater energy efficiency; embryonic markets, information, misaligned financial incentives, undervaluing energy efficiency.

Within UKERC, the project *Evaluating Energy Efficiency Programmes for Households* is being undertaken by the Technology and Policy Assessment theme. The aim of this project is to investigate whether household energy efficiency programmes result in real reductions in household energy use (Wade *et al.*, 2013).

UKERC activity related to the Transport and Industrial sectors have taken place; UKERC research has focussed on the modelling of transport demand (Brand *et al.*, 2012; Anable *et al.*, 2012), the role of policy instruments in accelerating the adoption of electric vehicles (Brand *et al.*, 2013) and heat recovery opportunities in UK industry (Hammond *et al.*, 2014).

Another area identified by the Carbon Plan is bioenergy. The role and benefits of bioenergy have been addressed in the UK Bioenergy Strategy (DECC, 2012d). The strategy recognised that “excluding biomass from the energy mix would significantly increase the cost of decarbonising our energy system”. However, it also stated that there are risks and uncertainties associated with bioenergy.

A review of the potential use of bioenergy was conducted by the UKERC Technology and Policy Assessment theme in research titled *Energy from Biomass: the Size of the Global Resource* (Slade *et al.*, 2011a). After reviewing over 90 studies with a focus on the global potential of biomass and bioenergy, it was concluded that replacing fossil fuel supply with biomass would not be practical or desirable. However, the total contribution of bioenergy to UK primary energy from 400 to 1100 PJ/year (4–11% of UK primary energy 2008) could be achieved by 2030 (Slade *et al.*, 2011a; 2011b).

The UKERC project on *Scenarios for the development of Smart Grids in the UK* sought to “advance understanding of smart grid deployment and utilisation through a programme of developing and evaluating a number of socio-technical scenarios”

(Balta-Ozkan *et al.*, 2014) The potential direction of smart grid development was explored, with the following core themes; security of supply, cyber security privacy and control, system fragmentation, electric vehicles and heat pumps, micro-generation and decentralisation, smart meters, and consumer distrust. The project identified a need to ensure equitable benefits across geographic areas and socio-economic groupings. Also, the need for consumer buy-in and the identification of "no-regrets" technology solutions was noted. Finally, the historically risk averse nature of network operators and the need for risk management across all actors was highlighted; the project synthesis report stated that "risk aversion was seen as the single most important barrier to smart technology investments."

Gas and electricity networks research is a crucial research area for the UKERC Energy Supply theme. The impact of smart metering on the electricity system though balancing and frequency response services were investigated (Chapter 3). The potential proliferation of large amounts of offshore renewables and their impact on network operation and design was an area that received attention within the UKERC Energy Supply theme. The analysis of greater interaction between European electricity systems was researched in the integration of electricity markets project (Chapter 3).

Energy security in particular is a topic that the UK and several other countries are increasingly anxious about, typical questions range from whether a low carbon future can maintain or even enhance energy security to if intermittent renewable generation can be adequately backed-up by traditional generators such as combined cycle gas turbines (CCGT) and, if so, at what cost.

Studies assessing the security and reliability of multi-vector energy systems are not well represented in the literature. Those that do exist do not explicitly model vital energy infrastructure such as the gas and electricity networks in detail. The interdependency between energy vectors is increasing and any one energy vector could adversely affect the capability of another. This emphasises the need for greater understanding of the reliability/security of integrated energy systems. The Energy Supply theme investigated the resilience and security of the UK gas and electricity networks using a probabilistic network model (Chapter 3).

UKERC held a workshop event exploring the 'future of the gas network'. This event brought together experts to discuss issues such as the role of gas networks as we move towards a decarbonised world. The key issues discussed were whether gas will still play a key role in the future (will it be used for energy balancing) or will others forms of energy be delivered via gas networks such as hydrogen or bio-methane.

One area where there has been controversy is the potential of shale gas in the UK. According to the British Geological Survey, the UK has potentially 37,600 billion cubic metres (bcm) of shale gas reserves. A study commissioned by DECC concluded that large-scale development of shale gas in the UK (at ~10% gas recovery rate) could lower long-term natural gas prices to 27% below current levels by 2020, saving the average household approximately £125 per year in lower gas costs. A future research agenda should explore, via modelling, the impact of shale gas alongside the overall future of the gas network in a decarbonised system.

The transformations required to meet the carbon emissions target whilst enhancing security of supply and maintaining affordability are challenging, more so given that policies will have to be designed to take into account the opinions of an increasingly engaged public. The UKERC research on public values, attitudes and acceptability (Parkhill *et al.*, 2013) highlighted key factors that influence public assessment of changes in energy system technologies and policies. It showed the public favours changes that are: energy efficient rather than wasteful; protect the environment; are reliable, accessible and safe; allow consumers a certain amount of autonomy.

Synthesis report objectives

The objective of this study is to draw together the emerging outputs, synthesise the outcomes of the research projects, identify the gaps in research and set the future research priorities of UKERC's Energy Supply theme.

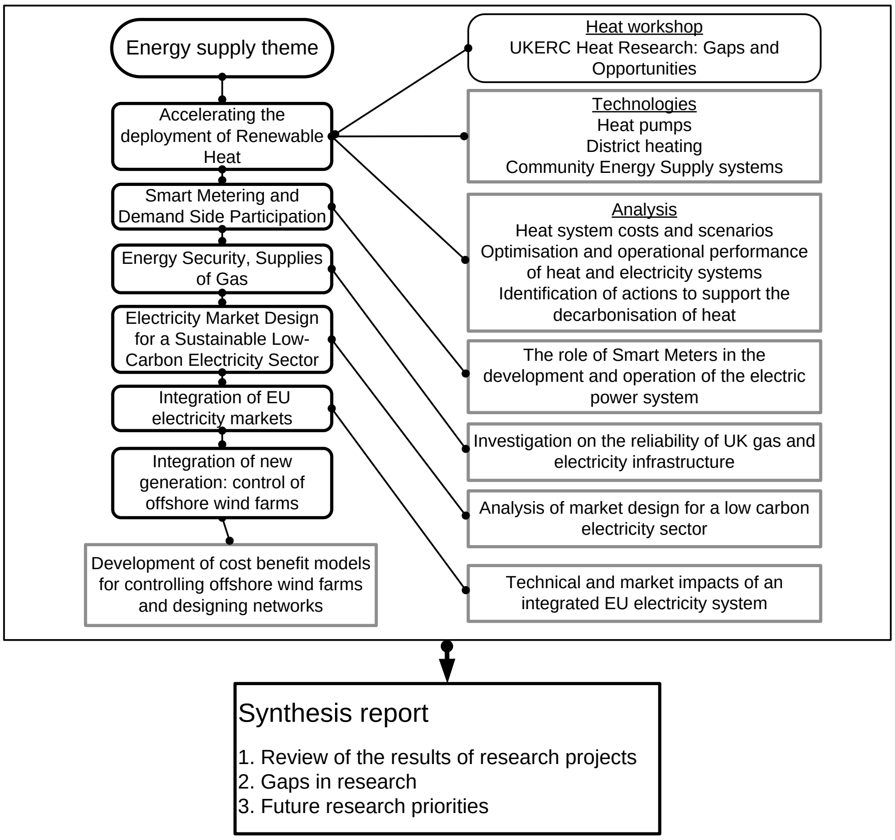


Figure 2: Energy Supply theme synthesis project flow diagram

The main research projects within the Energy Supply theme are shown in Figure 2: '*Accelerating the development of Renewable Heat*', '*Smart Metering and Demand Side Participation*', *'Integration of new generation: control of offshore wind farms'*, *'Integration of EU electricity markets*, '*Energy Security, Supplies of Gas'* and '*Electricity Market Design'* are reviewed in this report. Individual project analyses in conjunction with outcomes of the heat workshop and other research projects within UKERC will be used to identify the gaps and opportunities for further energy research (discussed at the end of every section).

2. Low Carbon Heat

2.1 Energy, Exergy and Exergoeconomics

Using only the concept of energy as a basis for analysis of energy conversion systems can give distorted results. This is because energy analysis is based on the First Law of Thermodynamics (FLT – the law of conservation of energy). Therefore, according to the FLT, two forms energy transfer, such as heat and work, are of equal importance. Thus, the calculation of work obtainable from an energy conversion system would not be possible using simple energy analysis only. To assess the system, the exergy approach should be used together with energy analysis. Exergy is work potential, or in other words, the maximum work delivered by a system which undergoes a reversible process. As work is the most useful form of energy transfer, exergy can be regarded as a measure of quality of energy.

High energy efficiency of a system does not necessarily mean that the energy is utilised effectively. For instance, high energy efficiency of an electric heater does not indicate that the energy conversion process is efficient from the point of view of thermodynamics, as high value electricity is converted to low value heat. In contrast, high exergy efficiency will always indicate that an energy conversion system operates efficiently. This implies that exergy analysis should be performed together with energy analysis for all energy conversion systems. Furthermore, in contrast to energy, exergy is destroyed during the energy conversion process. If exergy is destroyed in a system, the system becomes less capable of delivering work. An example is heat transfer, via a heat exchanger, from a high temperature fluid to a lower temperature fluid, where the work potential (exergy) of the high temperature fluid is reduced (destroyed).

To illustrate the usefulness of exergy analysis, consider two systems; firstly, a large tank of water (mass of about 1900 kg) at 30°C and secondly a barrel of hot water at 90°C (mass of about 270 kg). The energy transfer by heat from hot water to the environment at a temperature of 20°C is about 80 MJ for both systems. According to the Second Law of Thermodynamics (SLT) part of this energy could be converted to useful work. To calculate how much work could be obtained from both systems, exergy analysis should be conducted. Exergy analysis allows us to evaluate the work potential (or simply the quality) of both systems. In the example above only 3.3 % of the 80 MJ can be converted to work from the large tank whereas 19.3% can for the small barrel, i.e. the exergy of the large tank is 2.64 MJ and the exergy of the barrel is 15.44 MJ. Therefore, despite the fact that the first system is larger, its exergy (2.64 MJ), potential to produce work, is lower compared to the second system (exergy 15.44 MJ). In practical terms, if the sole purpose of both hot water tank systems were to supply heat energy for an energy conversion device to produce electricity, the second system (with higher exergy) would be favourable, as theoretically it would generate more electrical energy.

When energy conversion systems have more than one output (for example heat and electricity in CHP), to calculate costs of each product generated by a system and understand the cost formation process, exergy and economic analysis methods are integrated. This combined method – exergoeconomics – is often used to assess and optimise energy conversion systems.

Energy, exergy and exergoeconomic analysis methods have been used by the UKERC Energy Supply theme to analyse energy conversion systems and the results of these studies are presented in this report.

EXERGY

Exergy is the *maximum work* that can be obtained from a system or flow within the reference environment.

EXERGOECONOMICS

Exergoeconomics is the branch of engineering that combines exergy analysis and economic principles, when the exergy-costing principle is used. The exergy costing principle states that exergy is the only rational basis for assigning monetary values to the transport of energy and to the inefficiencies within a system. When using the exergoeconomic approach, other physical variables such as mass, energy or entropy should not be used for assigning monetary values (Bakshi *et al.*, 2011). Exergoeconomic analysis typically has two objectives; to calculate costs of thermodynamic inefficiencies in an energy conversion system and to calculate the production costs of final products. Exergoeconomic analysis gives a better guide to the relative value of electricity and heat than economic cost analysis.

2.2 Individual heating technologies

The Department of Energy and Climate Change (DECC) has identified a range of heating technologies which could replace existing gas boilers (DECC, 2013):

- Electrically driven heat pumps;
- Biomass systems: boilers and wood stoves;
- Solar thermal devices;
- Micro-CHP units based on Stirling engines or fuel cells with Organic Rankine Cycle systems;
- Electric storage heaters;
- Flue gas heat recovery systems;
- Domestic gas absorption heat pumps.

The implementation of these heating technologies is restricted by technological barriers (e.g. heat pumps can cause stress on the electrical power system), socio-economic barriers or lack of maturity (e.g. Stirling engine based CHP or fuel cells with Organic Rankine Cycle). Technological and socio-economic issues related to the implementation of alternative heating technologies, particularly heat pumps systems were investigated by the UKERC Energy Demand theme (Fawcett, 2011).

ORGANIC RANKINE CYCLE (ORC)

The Organic Rankine Cycle is a thermodynamic cycle which converts thermal energy into work. The ORC is based on traditional the steam Rankine cycle. However, instead of water, an organic high molecular mass fluid is used as working media. Due to the use of organic fluid the thermal energy at lower temperature can be converted to work. The main application areas of the ORC are biomass, geothermal and solar thermal systems.

SYNGAS

Syngas is synthesis gas, which typically contains hydrogen, carbon dioxide, carbon monoxide and may contain methane and water vapour. Syngas is produced using the gasification process from biomass or coal.

BIOGAS

A gas produced during the breakdown of organic matter in the absence of Oxygen. The typical method of biogas production is by the process of anaerobic digestion.

2.2.1 Heat pumps

Heat pumps have been identified as one of the key technologies which potentially could reduce carbon emissions from the domestic heating sector. However, the mass implementation of heat pumps will cause stress on the electricity infrastructure and will have a social and economic impact. The electrification of heating and the role of heat pumps have been addressed by the UKERC Energy Demand theme (Fawcett, 2011; Eyre, 2011). Other work, involving the analysis of impact of Heat pumps on electricity demand, is described in the "heat demand modelling" section of this report.

The project *The Future Role of Heat Pumps in the Domestic Sector* (Fawcett, 2011) aimed to explore technological, economic, social and energy supply factors which determine the benefits of heat pumps and looked at mechanisms for moving heat pumps from niche products to the mainstream. In the project, it was recognised that the installation of heat pumps in old poorly insulated houses will be problematic. The reasons for this include the lack of skilled installers. The analysis suggests that, for heat pumps to become mainstream (with lower costs and fewer social and technical barriers to installation), newer buildings with better insulation (15-20 year old) should be targeted first rather than old poorly insulated houses. Additionally, social landlords rather than private owners should be approached first, as they may be attracted to the lower running costs of heat pumps. The project concludes that although heat pumps are proven technology, suitable for the mass market, they are also expensive and disruptive and may only be relevant to a minority of householders.

HEAT PUMPS (HP)

A heat pump is a machine which transfers energy from a lower temperature thermal reservoir to a higher temperature reservoir. This is achieved by performing a thermodynamic cycle, which requires energy input.

Air Source Heat Pumps (ASHP) extract energy from outside air and transfers it directly to inside air or water. **Ground Source Heat Pumps (GSHP)** extract energy from the ground (soil, rock, underground water reservoir) and transfers it directly to inside air or water. **Exhaust Air Heat Pumps (EAHP)** extract energy from the exhaust air stream from the building and transfers it directly to inside air or water. The EAHP are used in buildings, where mechanical ventilation is installed. **Water Source Heat Pumps (WSHP)** extract energy from the surface water reservoirs (ponds, rivers, lakes, seas) and transfers it directly to inside air or water. The WSHP can be used to extract thermal energy from sewage and effluent water streams.

Five main challenges were identified and investigated in *Efficiency, demand reduction or electrification?* (Eyre, 2011); technical, social and behavioural, supply chain, electricity network and policy. The analysis indicated that conversion of the UK housing stock to electric heating would be “at best, extremely difficult, and, more likely, infeasible”. The project emphasised the need for further research to understand the role of heat pumps in the UK residential sector, in particular: performance in retrofitted buildings under various conditions, user acceptability, installer skills and practices and the impact on electricity grids.

To test the performance of heat pumps in real buildings a comprehensive field trial was conducted by the Energy Saving Trust (2010; 2013). The analysis showed that heat pumps can perform well in UK homes; the majority of customers were satisfied with hot water and heating provided by heat pumps.

To investigate the technical barriers for the implementation of heat pumps for individual buildings and their effect on the electricity network, research was conducted by the UKERC Energy Supply theme, *Power Requirements of Ground Source Heat Pumps in a Residential Area* (Bagdanavicius *et al.*, 2013). The objective of the project was to analyse the energy demand for space heating and domestic hot water systems, to analyse the electrical power requirement for heat pumps and to evaluate the impact of heat pumps operation on the electricity network. The main observations from the project are shown in Table 2.

A residential area of 96 two, three and four bedroom houses was considered. Energy demand and power requirements in old poorly insulated buildings and in new, well insulated, buildings were investigated. The requirement for electrical power for the heat pumps in the whole residential area was computed. The effect of room temperature settings, hot water use, heat pump thermal capacity and building insulation on the power requirements in the residential area was considered.

It was assumed that ground source heat pumps (GSHP) coupled with vertical ground loop heat exchangers were installed in each building. Two types of commercial GSHP with a nominal heat output of 6 kW and 10 kW were used to supply heat for space heating system and for domestic hot water systems. It was assumed that each heat pump had a 180 litre hot water tank and each tank was equipped with 3 kW immersion electric heaters.

Table 2: Conclusions and observations arising from the UKERC Energy Supply scheme paper; Power Requirements of Ground Source Heat Pumps in a Residential Area (Bagdanavicius *et al.*, 2013)

Temperature set-points:

- Reducing the night-time room temperature set-point (from +20° to +16°C) resulted in reduced electrical energy use. This was more pronounced in the poorly insulated buildings (9-15% reduction) than the newer buildings (2-7% reduction). The effect was also more pronounced in larger houses (6-15% reduction in the 4 bed compared with 2-10% in the two bedroom houses).
- The peak power requirements are not significantly affected by the reduction of the room temperature set-point during the night and during unoccupied periods.

Domestic Hot Water (DHW)

- In well insulated buildings, the electrical energy used for DHW is higher than that used for heating.
- Energy demand increases during the morning and evening are mainly due to the increase in hot water consumption.

Peak Demand

- Peak power requirements are not significantly different (insulated vs. poor insulation); the use of hot water tanks for DHW systems does not help to circumvent this problem.
- The maximum peak electrical power in the entire modelled residential area is about 20% higher when heat pumps with a nominal heat capacity of 10 kW were used than with 6 kW heat pumps, implying that the capacity of the heat pumps has a significant effect on peak power.

Total Energy Use

- Energy demand of well insulated buildings is much less compared with poorly insulated buildings.
- Use of more powerful heat pumps did not affect the total energy consumption

Electricity Network

- Heat pumps will have a significant impact on the electricity network
- The estimated total peak electric power for heat pumps in all 26.3 million residential houses in the UK would be 49-63 GW (34 GW without DHW) on the coldest morning.

Based on the research conducted by UKERC and heat pump field trials, several technical and socio-economic challenges have been identified:

Technical challenges:

- How does the control strategy of heat pumps affect the electricity network?
- How can load shifting strategy be applied to reduce the peaks resulting from the operation of heat pumps?
- What is the role, if any, of smart meters in smoothing the impact of heat pumps?
- What percentage of the national housing stock would be technically suitable for heat pump installation, now and in the future?
- What is the effect of load shifting on the room temperature and how it could affect customers' satisfaction?

- What is the impact of heat pumps on electricity infrastructure due different hot water consumption patterns in well insulated buildings?
- What is the role of thermal storage in heat pump systems?

Socio-economic challenges:

- Where are the most promising niches for heat pumps within the existing housing stock?
- How can low temperature heating systems be installed in existing homes at least cost and with least disruption?
- What is the risk that mass installation of heat pumps would increase the summer cooling demand?
- What are householder experiences of heat pumps, particular when retrofitted into older homes?
- How can a small-scale and fragmented heat pump installer industry transform into a sector capable of delivering high quality installations in large numbers?

2.2.2 Micro-CHP systems

Micro-CHP systems can potentially be used as substitute for existing gas boilers in individual houses and in small commercial applications. Micro CHP technologies can be divided into two groups: fuel cells and technologies based on thermodynamic cycles. Microgeneration technologies based on thermodynamic cycles include internal combustion engines, gas turbines, organic Rankine cycle systems and Stirling engines.

To investigate the performance of microgeneration CHP systems field trials were conducted by the Carbon Trust (2011). Two CHP technologies, one based on Internal Combustion engines and another based on Stirling engines, were tested. It was reported that, using the domestic Stirling engine micro-CHP systems, a carbon saving of around 5% can be achieved in individual households. In households with higher heat demands, the Stirling engine micro-CHP systems performed better, with a potential carbon saving of around 9%.

A project, *Economic an Exergoeconomic Analysis of Micro GT and ORC Cogeneration Systems* (Bagdanavicius *et al.*, 2012a), was conducted by the UKERC

Energy Supply theme. Two energy technologies were analysed; a gas turbine micro-CHP (micro-GT) system and a gas turbine micro-CHP unit combined with an Organic Rankine Cycle turbine (micro-GT-ORC), see Figures 3 and 4, and Table 3. Note that the rated output from the units is over 100kW (both thermal and electric) – this implies that the analysed systems are of community, as opposed to single household scale. However, with the development of small-scale gas turbine micro CHP systems (Micro Turbine Technology BV, Netherlands) similar analysis methods could be used for single household micro CHP systems.

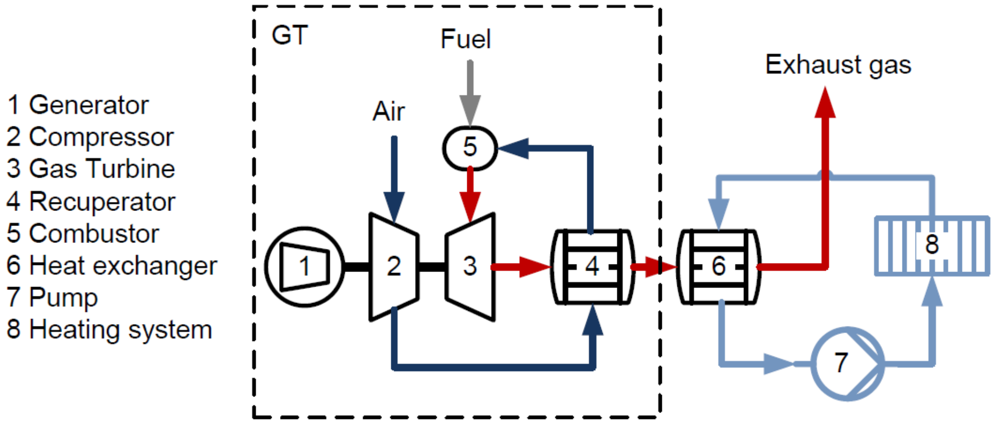
Table 3: Data for the analysed Micro-CHP systems

Parameter	Micro GT	Micro GT-ORC
Fuel energy (HHV), kW	369.7	369.7
Electrical output, kW	102.1	112.1
Thermal output, kW	157.6	148.0

The calculated energy efficiency of both systems is about the same (around 70% – See Table 4). However, the micro-GT-ORC system is more exergy efficient than the micro-GT. This implies that the primary energy, in this case natural gas, is consumed more efficiently – as more high quality energy, electricity, is generated.

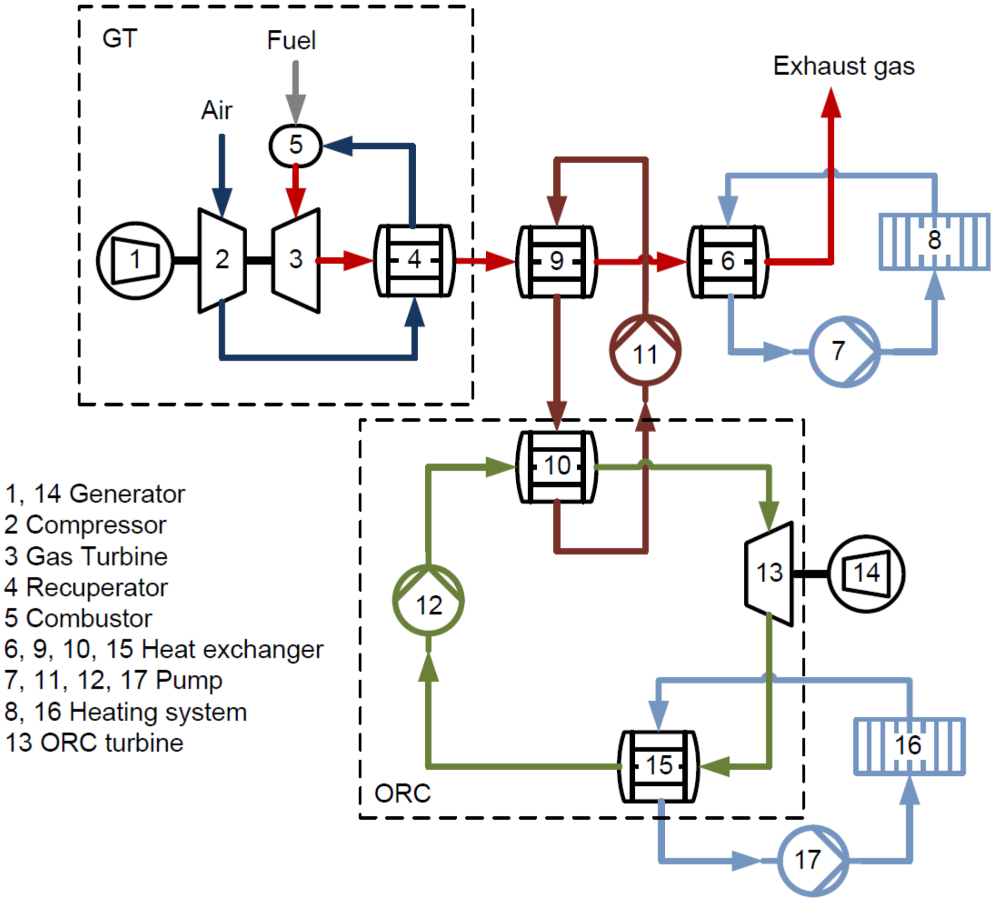
Table 4: Calculated Energy and Exergy Efficiencies for MicroGT and Micro-GT-ORC systems

	Micro-GT	Micro-GT-ORC
Electric energy efficiency[1], %	27.5	29.9
Heat energy efficiency, %	42.6	40.0
Total energy efficiency, %	**70.1**	**69.9**
Electric exergy efficiency[1], %	29.3	31.8
Heat exergy efficiency, %	6.2	5.8
Total exergy efficiency, %	**35.5**	**37.6**



System ambient air is compressed using compressor (2), preheated in recuperator (4) and used for burning fuel in combustion chamber (5). Hot gases (red arrow) expand in turbine (3) and after the expansion are used to preheat incoming cold air stream in recuperator (4). Exhaust gas (red arrow) after the recuperator (4), is used to heat water for the heating system in an exhaust gas exchanger (6). The heated water (light blue arrow) is pumped to the building heating system (8). Electricity is generated in generator (1) by rotating turbine (3).

Figure 3: Schematics and operation of a Micro-GT system



System hot exhaust gases after recuperator (4) are used to heat intermediate fluid (brown lines) in a heat exchanger (9). Intermediate fluid transfers heat the from the hot exhaust gases to the working fluid (green lines) of the ORC system. Thus, the intermediate loop combines two separate systems: gas turbine cycle and ORC cycle. In the ORC system the working fluid (green line) evaporates in heat exchanger (10) and expands in ORC turbine (13). The temperature of the fluid after ORC turbine (13) is sufficiently high for heating water in a heating system (16). Condensed fluid after heat exchanger (15) is pumped back to the heat exchanger (10) and the cycle repeats. In micro-GT-ORC system electricity is generated in generators (1) and (14) and heat to the heating system is transferred from heat exchangers (6) and (15).

Figure 4: Schematics and operation of a Micro-GT-ORC CHP system

Based on the research projects conducted by the Energy Supply theme several future research areas were identified:

- The operation of micro-CHP as at buildings level
- The impact of micro-CHP systems on electricity networks.
- Development of small smart energy networks using micro-CHP and other low carbon heating technologies.
- Development of biomass micro-CHP technologies
- The role of energy networks with thermal storage and micro CHP in demand-supply balancing.

2.3 Heating technologies at network level

HEAT NETWORKS (DISTRICT HEATING)

Heat networks are the energy infrastructure used to supply heat directly to homes and businesses through a network of pipes from a central source. Water is traditionally used as an energy carrier.

COOLING NETWORKS (DISTRICT COOLING)

Supply cold water directly to buildings (where cooling and air conditioning is required) through a network of pipes from a central source.

Thermal energy infrastructure systems are often called **DISTRICT HEATING AND COOLING (DHC).**

It has been recognised by the Department of Energy and Climate Change that one of the alternatives to gas and electricity use in individual buildings is to develop district heating networks (DHN) (DECC, 2012b). It is believed that “heat networks have the potential to play a significant role in the UK energy mix” and that district heating schemes can contribute to (DECC, 2012b; Aberdeen Heat and Power, 2014):

- reduction of carbon emissions;
- reduction of fuel poverty;
- provision of energy security;
- reduced dependency on fossil fuels.

District Heating Networks can only realise these benefits if long term low carbon heat sources are available and if they are capable of meeting average and peak heat demand without dependence on fossil fuels. To be able to develop district heating networks, a number of challenges must be addressed (DECC, 2012b):

- the risk of no low carbon heat sources being available;
- infrastructure and disruption caused by construction;
- price, contract issues and public attitudes;
- heat networks that can serve the peaks of winter demand and remain low carbon;
- the risk that a heat network builds in inefficiencies.

The European association *Euroheat and Power* and *District Heating and Cooling Plus Technology Platform* have published a “Strategic Research Agenda” (Euroheat and power, 2012), where technical and socio-economic research priorities for District Heating Networks are identified. The identified options include:

- Integration of various thermal energy sources in District Heating and Cooling systems;
- Using District Heating and Cooling as a buffer for excess electricity generation;
- Integration of energy networks to couple local supply with energy demand;

The importance of integration of different energy vectors has been also noted by the European Technology Platform *Renewable Heating and Cooling (RHC, 2013)*. The RHC is an industry led stakeholder forum which brings together stakeholders from the biomass, geothermal and solar thermal sectors to define a common strategy for increasing the use of renewable energy technologies for heating and cooling. In their “Strategic Research and Innovation Agenda for Renewable Heating and Cooling” (*RHC, 2013)* the need for integration of thermal systems into smart thermal/electrical grids was emphasised.

The integration of different energy networks leads to the development of more complex infrastructure systems – district energy systems. Portions of these complex structures become interdependent and interact with each other. To investigate district energy systems, several research projects were undertaken, these are summarised in Table 5:

Table 5: UKERC district energy system projects

Title	Description
Assessment of community energy supply systems using energy, exergy and exergoeconomic analysis (Bagdanavicius *et al.*, 2012b)	Assessment and comparison of different heat and electricity generation systems using thermodynamic analysis methods.
Energy consumption and economic analyses of a district heating network (Pirouti *et al.*, 2013)	Analysis of various designs of a district heating network and development of a method to allow the design of more efficient and cost effective district heating systems.
Multi-vector energy systems (Rees et al., 2014; Liu, 2013)	Analysis of newly built multi vector energy supply schemes. Development of a methodology for design optimisation of combined electricity and heat networks.
Exergy and exergoeconomic analysis of a Compressed Air Energy Storage combined with a district energy system (Bagdanavicius *et al.*, 2014)	Analysis of the potential for using heat generated during the compression stage in a Compressed Air Energy Storage system.

2.3.1 Community CHP systems

The aim of the project, *Assessment of community energy supply systems using energy, exergy and exergoeconomic analysis* (Bagdanavicius *et al.*, 2012b) was to perform a comparative study of different CHP plants using advanced thermodynamic analysis methods. Four systems were studied: Biomass Steam Turbine CHP plant (BST), Gas Turbine CHP plant using natural gas (GT), Biomass Integrated Gasification Gas Turbine CHP plant (BIGGT) and Biomass Integrated Gasification Combined Cycle CHP plant (BIGCC). Schematics and process descriptions are shown in Figures 5-8.

The underlying assumptions were:

- 10 % return on investment,
- 20 years investment repayment period,
- 7000 hours annual operating hours,
- operation and maintenance costs are not included,
- 2.05 ¢/kWh fuel price (HHV) based on natural gas for industrial consumers in UK.
- The total capital costs:
    - BST system – M€ 5.14,
    - GT system – M€ 3.46,
    - BIGGT system – M€ 17.01,
    - BIGCC system – M€ 21.57.

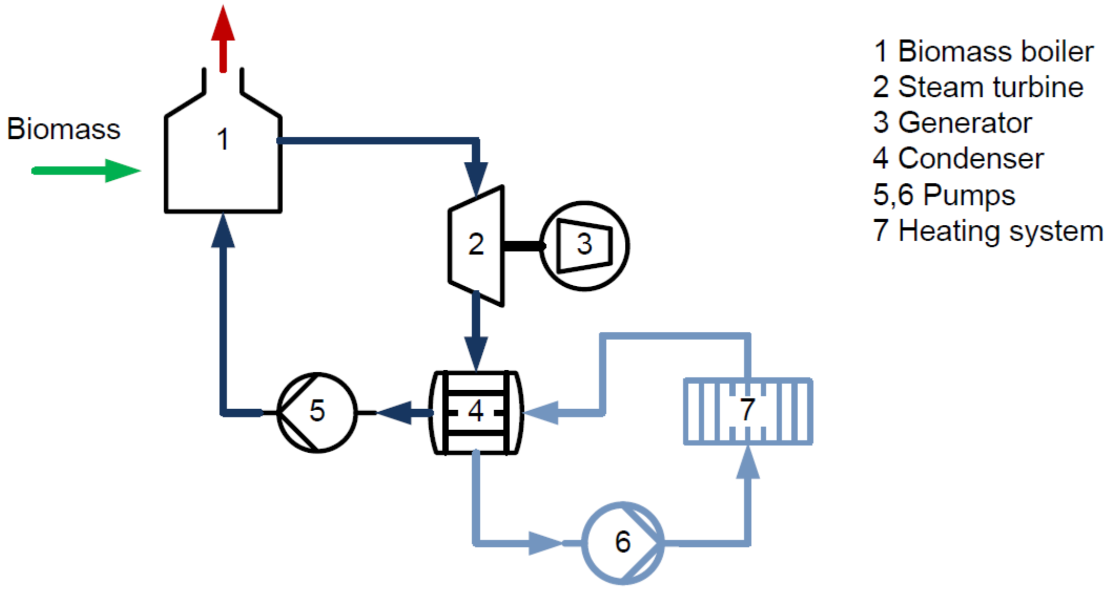
Energy efficiency analysis of CHP systems showed that all four systems have similar energy efficiencies (see Table 6). However, exergy analysis shows that the GT and BIGCC CHP systems are more exergy efficient compared with the BST and BIGGT systems. The gasifiers and combustors are the energy system components responsible for high exergy destruction and for the significant increase in the exergy costs of products (see Figure 9).

The exergy cost of biomass fuel and natural gas are almost the same. In the BST systems the exergy cost of electricity and heat are almost identical. In the GT and BIGGT system the electricity exergy cost is considerably lower than that of heat. This indicates that the gas turbine electricity generation costs are lower. Higher heat exergy costs in the GT system is related to the large exergy destruction rate in the heat exchangers, where high temperature exhaust gas is used to increase the temperature of a district heating system.

The increase of exergy costs in the BIGGT and BIGCC systems compared with the GT systems is related to the additional exergy destruction in the gasifiers and large capital investments. Large heat exergy cost in the BIGGT system is associated with large exergy destruction in heat exchangers, where high temperature syngas and exhaust gas is used to heat water in the DH system. This problem is avoided using the BIGCC system, where the combined cycle is implemented. The exergy cost of heat in the BIGCC is similar to that of the BST system.

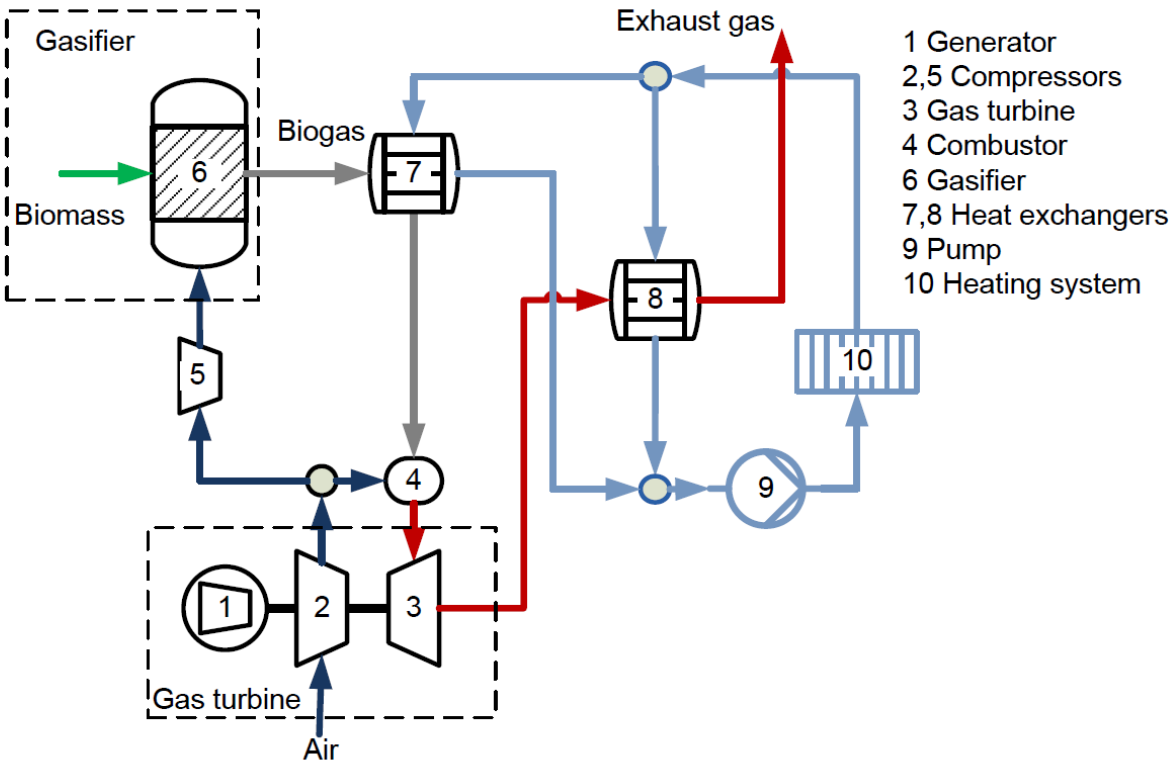
Table 6: Energy and exergy efficiencies of community energy systems

	Energy efficiency	Exergy efficiency
BST	84.5 %	24.3 %
GT	83.6 %	40.0 %
BIGGT	85.6 %	32.3 %
BIGCC	85.2 %	39.9 %



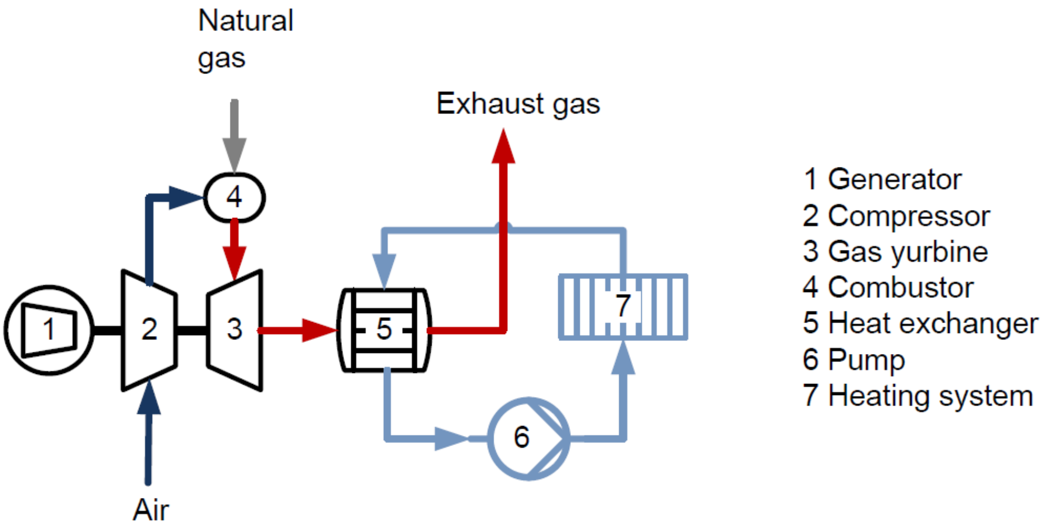
During the heating season the steam at higher temperature and pressure is delivered to the heat exchanger (4), where it is condensed and district heating water is heated.

Figure 5: Schematic and process description of a Biomass Steam Turbine CHP system (BST).



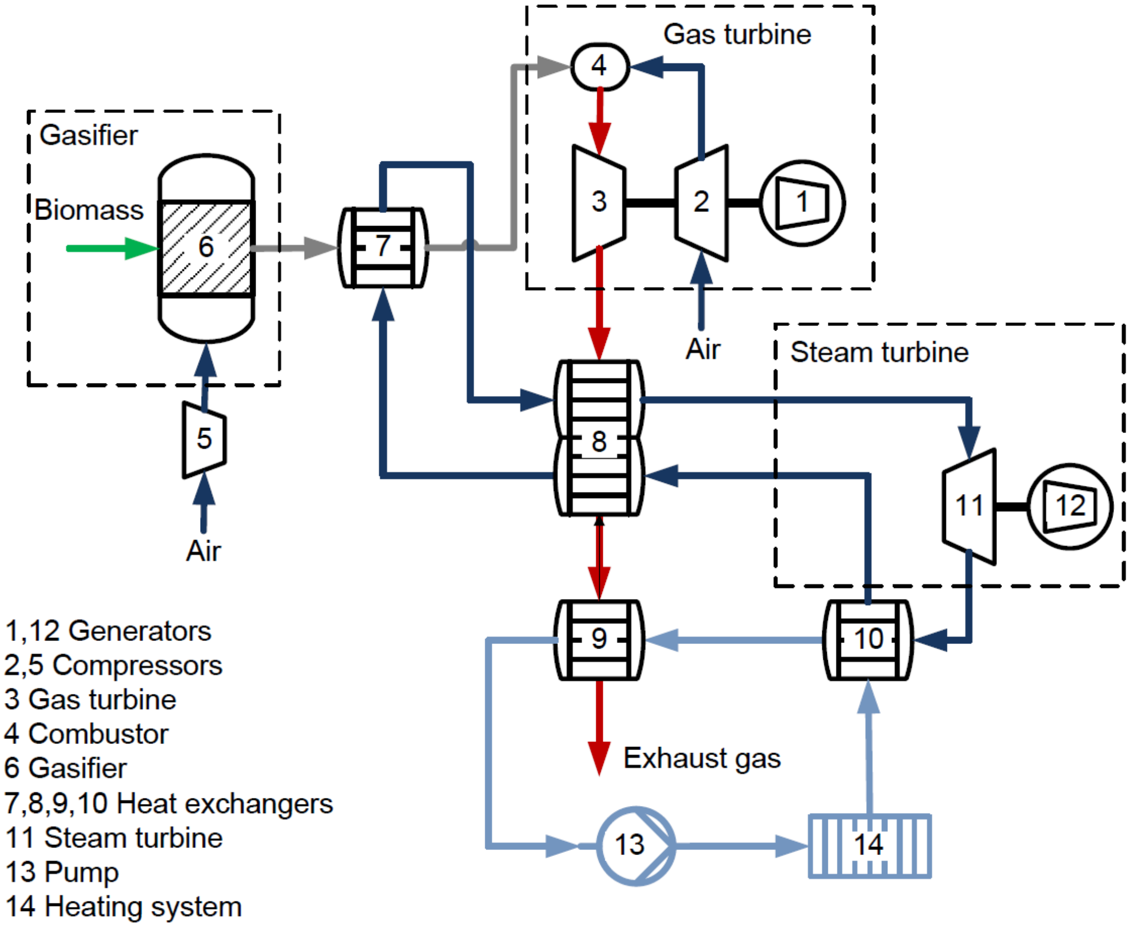
Biomass is supplied to the gasifier (6). The main gas turbine compressor (2) is used to deliver air to the combustion chamber (4). About 10% of total air supplied by the compressor (2) is used in the gasification process. The auxiliary compressor (5) pressurises air to the required 18 bar pressure. Syngas leaves the gasifier and is cooled down from 850°C to 400°C in the heat exchanger (7). Cooled high pressure gas is supplied to the combustor (4). Hot flue gas expands in the gas turbine (3) generating electricity. Then hot flue gas is cooled in the heat exchanger (8). Heat exchangers (7 and 8) are used to heat district heating water.

Figure 6: Schematic and process description of a Biomass Integrated Gasification Gas Turbine CHP plant (BIGGT).



Natural gas is used as fuel in the combustor. Burned flue gas expands in the gas turbine and then is delivered to the heat exchanger (5), where the district heating fluid is heated.

Figure 7: Schematic and process description of a Gas turbine CHP system (GT).



Hot syngas is cooled from 850°C to 400°C in heat exchangers (7 and 8) where steam is produced. Cooled gas is delivered to the combustor (4), expands in the turbine (3) and cools to 120°C in the heat exchanger (8) and heat exchanger (9). Steam produced in heat exchanger (8) is supplied to the steam turbine (11). Exhaust steam at 1.1 bar pressure is delivered to the heat exchanger (10) where it condenses. District heating water is heated by the exhaust the flue gas from the gas turbine in the heat exchanger (9) and by the condensing steam in the heat exchanger (10).

Figure 8: Schematic and process description of a Biomass Integrated Gasification Combined Cycle CHP plant (BIGCC).

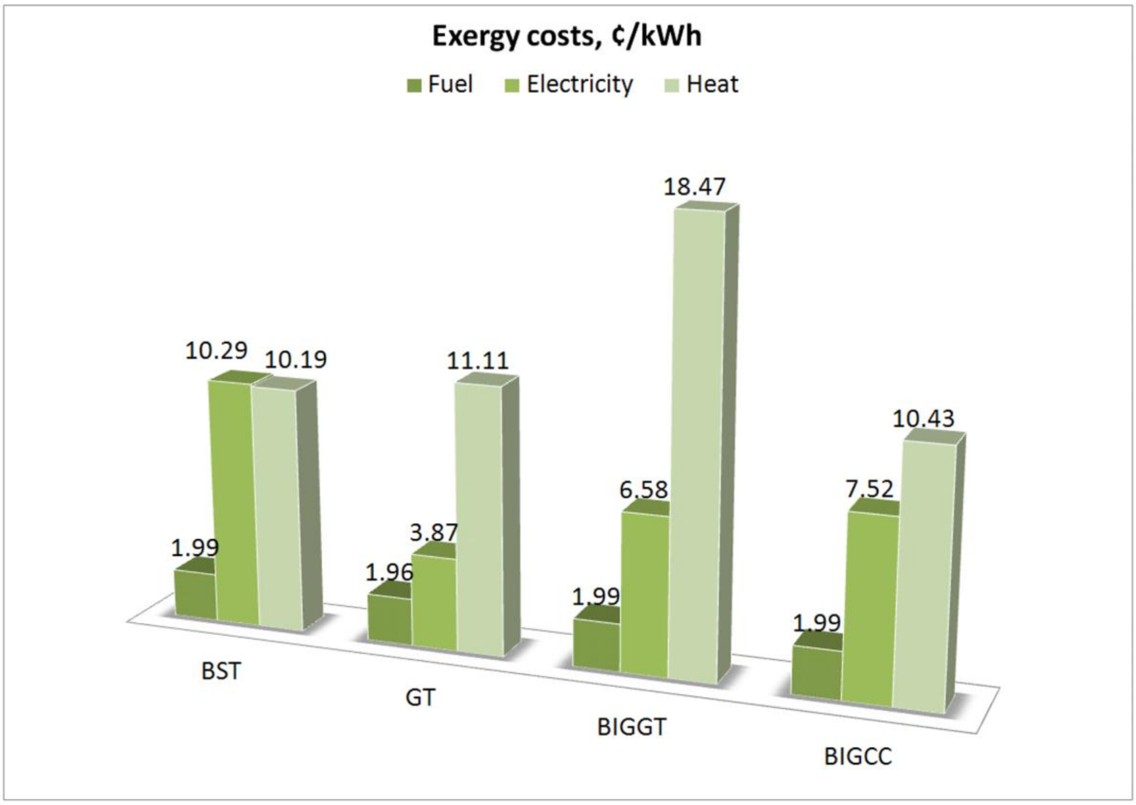


Figure 9: Exergy costs (Euro cents per kWh) of electricity and heat.

The Biomass Integrated Gasification Combined Cycle CHP system and the Gas Turbine CHP system, which operates using natural gas, have the highest exergy efficiency. BIGCC-CHP systems are relatively complex – they may, therefore, be seen as riskier by potential investors/adopters. However, pilots BIGCC-CHP schemes, such as the demonstration plant in Varnamo, Sweden (Stahl *et al.*, 1998), show the potential.

Biomass CHP technologies, other than BIGCC-CHP, have lower exergy efficiencies. This indicates that the chemical energy of biomass fuel is not effectively utilised to produce electricity and heat; implying that existing biomass CHP systems must be improved to achieve higher exergy efficiencies.

Exergoeconomic analysis has shown that, due to the use of the biomass gasification process, the exergy efficiency reduces and the exergy costs of electricity and heat increases. The increase of exergy costs is related to the additional costs of gasifiers. Therefore, to reduce the costs and increase the efficiency of direct biomass CHP systems, research in the area of direct biomass combustion in gas turbines is needed.

Based on this research, the following areas for further research were identified:

- Further development of simplified exergy and exergoeconomic analysis methods for use by decentralised and community energy systems planners and designers.
- Investigation of direct or indirect use of biomass in gas turbines.
- Development of medium and large scale smart community energy systems, taking into account technical and economic issues related to utilisation of renewable energy sources, including solar thermal energy and biomass.

2.3.2 District heating networks

Heat networks have the potential to play a significant role in the UK energy mix (DECC, 2012b). Using District Heating Networks (DHN) primary energy savings can be achieved, especially where heat and electricity are generated in a single CHP unit or waste heat from existing power plants is recovered. In addition, DHNs have the flexibility to accommodate heat from a variety of renewable heat sources including: biomass, solar thermal and geothermal.

The high cost of DH is mainly attributed to the capital cost of the hot water pipe network. The cost of DH pipe network depends on the pipe length and diameter. If the DHN network is oversized the total installation costs increase, while an undersized DH network may also significantly increase the operating costs.

Heat losses in a DH network are affected by pipe diameters and the insulation material, as well as the temperature of the heat carrier medium in the supply and return pipes. Pipe diameters also have an impact on pressure loss of flowing fluid and consequently on the electrical energy consumption of pumps and heat losses. As a result, special attention has to be paid to the determination of pipe diameters as well as the way the system is operated.

Pressure loss per unit length of pipe is an important design parameter used for designing DHN. As a rule of thumb, many DH networks in Denmark and in other European countries are designed using the pressure loss of 100–200 Pa/m at maximum heat demand. However, the maximum heat demand may last a very short period of time during the heating season. Therefore, the pipe network is oversized the most of the time.

To investigate the effect of different pressure loss values on the performance of district heating networks (DHNs), a project titled *Energy consumption and economic analyses of a district heating network* (Pirouti *et al.*, 2013) was conducted. The objective of the project was to assess different design cases of district heating network (DHN) and to find the optimum DHN system, where the energy consumption is minimal and the capital and operating costs are the lowest.

A development project in Ebbw Vale, South Wales was used as a case study to perform analysis of DHN systems. Maximum heat demand was calculated for each consumer. Energy demand for space heating and domestic hot water was found based on the estimated area and heat load density for each building, taking into account outdoor air temperature variation. Several regimes of supply and return temperatures were considered – 120°/70°C, 110°/70°C, 100°/70°C and 90°/70°C. Pipes were selected assuming the maximum mass flow rate and design pressure loss values. The pressure loss values for the calculation were taken from 50 to 1200 Pa/m with a step change of 50. In total, 18 different pipe networks for each temperature regime were designed.

The project consisted of two stages. First, the modelling of the DHN using commercial software was conducted. Then a two-stage model designed DHN cases was developed. Using this model, the simulation of DHN cases over the year was conducted and energy and economic analysis performed to calculate the DHN cases with minimum annual total energy consumption and minimum annualised cost. The aim of the simulation was to select a predesigned case with minimum total annual energy consumption or cost by selecting suitable pump and pipe sizes, taking into account different parameters such as target pressure loss, temperature regime and operating strategy.

In DHNs, to supply heat to consumers according to energy demand, two parameters can be controlled: supply temperature and flow rate of energy carrier. To investigate the effect of these two variables on the DHN, simulation of the performance of designed DHN systems was conducted using four different operating strategies:

- Constant flow and constant supply temperature (CF-CT). System operated at the maximum heating load, maximum temperature and maximum flow rate.

- Constant flow and variable supply temperature (CF–VT). It was assumed that the flow rate was constant and supply temperature of the energy carrier was controlled according to the heat demand.
- Variable flow and constant supply temperature (VF–CT). It was assumed that supply temperature was constant, but the flow rate varied according to the heat demand over the year. Therefore, the pressure drop and the required pump head varied accordingly.
- Variable flow and variable supply temperature (VF–VT): The VF–VT is the combination of CF–VT and VF–CT operating methods. Control variables, flow and supply temperature were adjusted simultaneously with respect to the variation of heat demand. For this operating strategy to obtain optimum supply temperature and flow rate were optimisation was used.

It was shown that the operating strategy and the supply and return temperature regime have substantial impact on equivalent annual costs. The DHN control strategy has an impact on system efficiency. For high temperature DHNs, the Variable Flow Variable Temperature control method is better than other methods. For low temperature DHNs, Variable Flow Constant Temperature control strategy should be used.

Analysis of the DHN system shows the importance of the proper design of the pipe network. Diameters of pipes, chosen operating temperatures and control mode have considerable impact on capital investment and operating costs of DHN. Therefore, the determination of the optimal pipe and pump sizes is crucial. It was found that the minimum annual total energy consumption and the minimum equivalent annual costs were obtained using relatively small pipe sizes with large pressure drops.

Based on the research conducted by the UKERC Energy Supply theme on DHN, the areas for further research were identified:

- Further development of DHN optimisation methods for large networks consisting of branches and loops is needed.
- Investigation on variations of heat demand and the effect on the operation and design of DHN taking into account the occupancy type, consumer

behaviour, diversity factor (the ratio of total expected load and maximum possible load) and outside temperature variations are required.

- In a DH, network pumps are sized to overcome pressure loss along the route with maximum pressure drop. Branches or pipe sections located closer to the heat source experience a much higher differential pressure. Therefore, pipe diameters of these branches can be reduced further to match the differential pressure available at the branch connection to the main pipeline point. Consequently, the capital investment and heat losses of the DH pipe network decrease. Analysis of how the design of DHN using variable pressure losses for pipe selection can improve economics of DHN is needed.
- There is also a need for more research on business models / local policies to provide incentives for district heating schemes.

2.3.3 Multi vector community energy systems

Any cost effective design of an energy supply scheme, adhering to carbon emission constraints, requires an understanding of available technologies and an assessment of the energy related emissions. A whole scheme approach to the design is necessary to identify the optimal combination of technologies and infrastructure to meet the energy demand. In the project *Carbon constrained design of energy infrastructure for new build schemes* (Rees *et al.*, 2014) a design tool that determines the optimal mix of energy supply technologies and the energy network infrastructure for community energy schemes, subject to local emission reduction targets, was developed (see Figure 10). The optimisation objective was to minimise the cost of build to the developer of the new build scheme. An example case study was used to illustrate the application of the tool for the carbon constrained energy infrastructure design of a UK community.

The developed tool determines the optimal design of an energy supply scheme for a new build community. The model determines the type and capacity of energy supply technologies to be installed (both at the buildings level and network level) at the new build scheme and the electricity/gas/heat network infrastructure required.

As an example, a new redevelopment scheme in Ebbw Vale, South Wales, was considered. The scheme consisted of residential buildings, schools, leisure facilities and a local hospital. The project set a 60% target reduction of regulated emissions relative to a benchmark defined as all buildings built to 2006 Part L standards and supplied using natural gas boilers and grid supplied electricity. Diverse projections for the average (CEF_{Avg}) and marginal (CEF_{Marg}) carbon emissions factors for grid supplied electricity were used. The optimal energy supply scheme that delivers the required emissions performance was determined for three design cases. The solver outputs are summarised in Table 7.

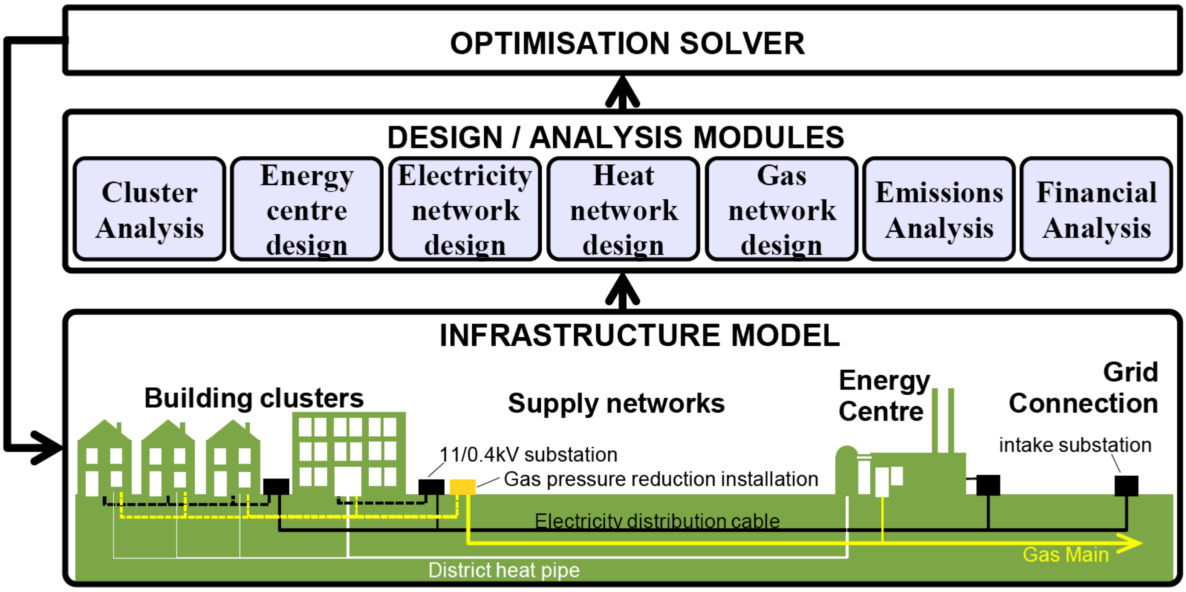


Figure 10: Structure of the integrated design tool (Rees *et al.*, 2014).

Table 7: Summary of findings for the different cases input to the multi vector optimisation program

Case	Aims	Resulting scheme features
Reference	The reference case provided the benchmark for the cost to the developer	Nat Gas CHP : None Heat Network: None Heat pumps: None Local Gas Boilers: Yes Solar Thermal : 2. None Solar PV: 1. None Total Cost to Developer: £5.210m.
Case A	To evaluate the optimal infrastructure design for the same scheme with both the CEF_{Avg} and CEF_{Marg} set to projections by (DECC, 2010b)	Nat Gas CHP : 2.4MWe Heat Network: Yes Heat pumps: ASHPs, GSHPs Local Gas Boilers: No Solar Thermal : 2.47MWth Solar PV: 1.5MWe Total Cost to Developer: £23.235m.
Case B	To analyse the sensitivity of the solution to the starting year of the analysis period. The case study was carried out by changing the start of the 20 year analysis period to 2020.	Nat Gas CHP : None Heat Network: None Heat pumps: Yes Local Gas Boilers: No Solar Thermal : 4.03MWth Solar PV: 372kWe Total Cost to Developer: £20.151m
Case C	To test the sensitivity of the optimal solution to the projections of grid carbon emissions intensity, a different CEF_{Marg} was used (Zero carbon Homes CEF_{Marg})	Nat Gas CHP : None Heat Network: Relatively small Heat pumps: None Local Gas Boilers: Yes Solar Thermal : Yes Solar PV: Yes Total Cost to Developer: £12.868m

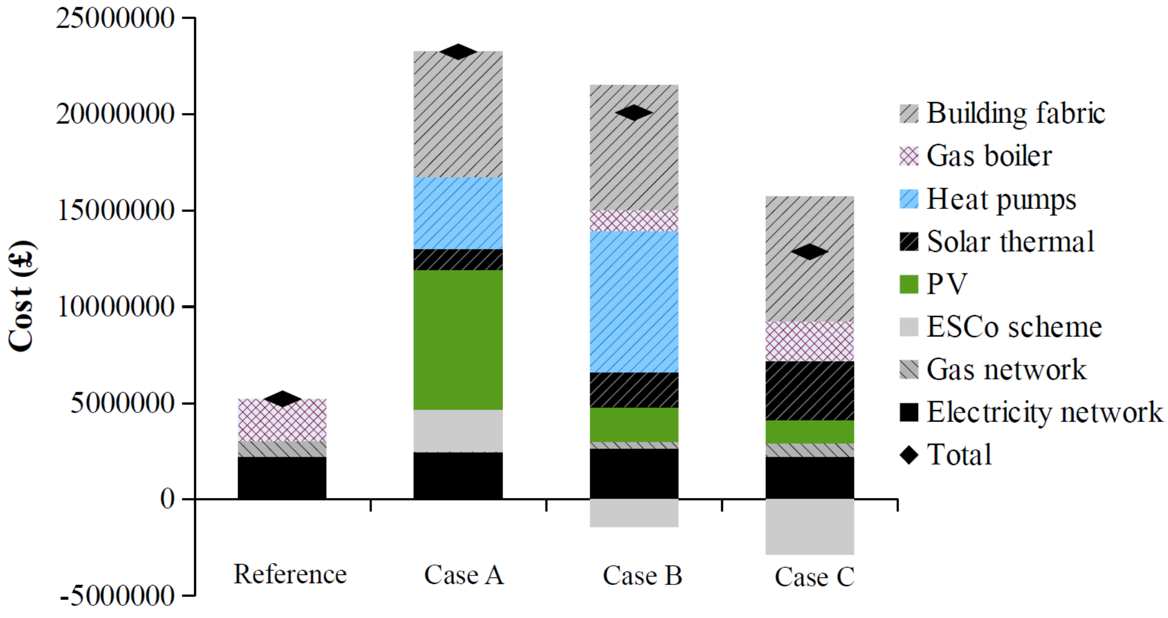


Figure 11: Comparison and breakdown of the total cost of each design case considered

It was shown that the optimal solution changes significantly with the assumed year of build completion. This results from the interdependency between the reductions of on-site emissions achieved using technologies such as PV, CHP and Heat pumps and the emissions intensity of electricity supplied from the grid.

The optimal design is sensitive to the projected emissions factor for grid supplied electricity. Several issues arise from the lack of consensus upon the choice of CEF projection – including a significant capital overspend if the use of high capital low carbon technologies such as PV is overprescribed and the possibility of developers cherry picking a projection that favours the use of a particular technology (Figure 11). This highlights the necessity for establishing a consistent approach for estimating a projection of the marginal emissions factor for grid supplied electricity.

2.3.4 Energy storage

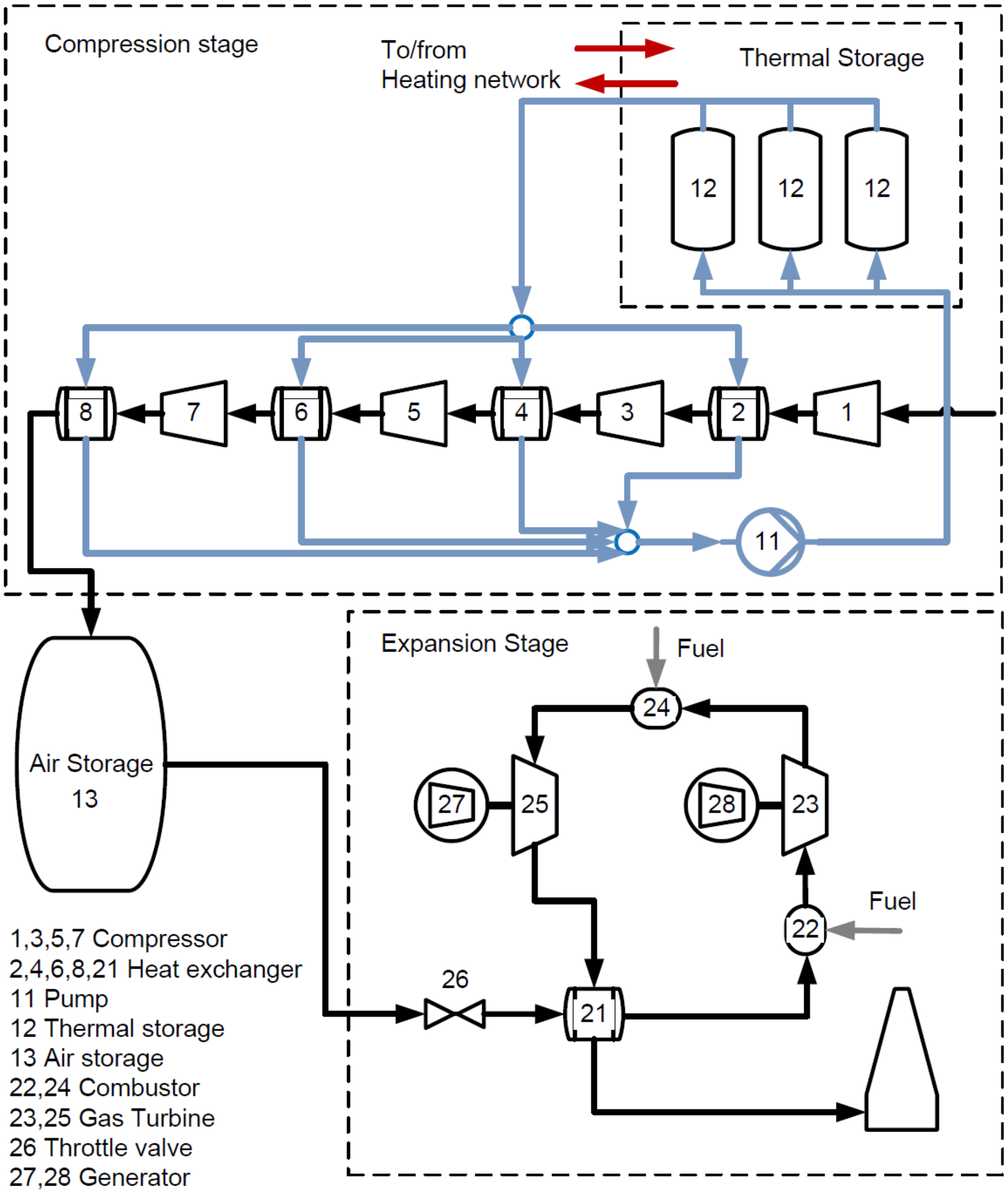
The capacity of electricity generation from renewable energy sources has been steadily increasing over the last decade. Wind power and solar PV were the fastest growing renewable energy technologies in Europe in 2012. Due to the intermittent nature of wind and solar energy, new solutions are sought to enhance the reliability of the electricity supply. Energy storage has been identified as one of the solutions to limit the capacity required for generation reserve.

A candidate energy storage technology is Compressed Air Energy Storage (CAES). The distinctive feature of CAES, compared with other energy storage systems, is the production of large quantity of heat during the compression stage. This heat can be stored and used as an energy source for heating. UKERC thermal storage research has been carried out by Eames (Eames *et al.*, 2014).

The objective of the project *Exergy and exergoeconomic analysis of a Compressed Air Energy Storage combined with district energy system* (Bagdanavicius *et al.*, 2014) was to analyse the potential for using heat generated during the compression stage in Compressed Air Energy Storage system using exergy and exergoeconomic analysis (Figure 12). Two systems were investigated; Compressed Air Energy Storage (CAES) and the same size Compressed Air Energy Storage combined with Thermal Storage (CAES-TS). In the second system, heat generated during the compression cycle was used to charge thermal energy storage systems, connected to a district heating network.

Heat is wasted in CAES systems. The calculated energy and exergy efficiency of the CAES is identical to the electrical efficiencies of the CAES-TS. The overall energy efficiency of the CAES-TS (85.8%) is considerably higher than the CAES system (48.4%). The exergy efficiency of CAES-TS is 55.8% and CAES is 50.1%.

The project showed that the CAES systems combined with Thermal Storage have potential, both as energy storage and as a heat source for district heating systems. Due to the intermittent nature of wind and solar energy CAES-TS could be used as a tool for balancing overall energy demand and supply. However, more research is required to analyse how gas can be replaced with renewable energy and develop new CAES-TS systems. Such modified combined energy storage systems could be used for energy storage, heating and cooling of residential and commercial buildings. A further area for future research is the analysis of energy storage systems integrated within a community energy supply system. This is will allow insights into how storage systems could operate as part of a community energy system.



Four compressors (1, 3, 5 and 7) are used to pressurise air from ambient pressure to about 82 bar pressure. In the first compression stage (1) the air is pressurised to about 4.5 bar pressure. After this compression the air temperature increases to about 210°C. Air is cooled in the heat exchanger (2) to about 50°C and enters the next compressor. In the second, third and fourth stages (3, 5 and 7) air is compressed to 16, 41 and 82 bar pressure. The compressed air temperature rises to 220°C after the second compressor, 170°C after the third compressors and 140°C after the fourth compressor. After each compression stage the air is cooled to 50°C in heat exchangers (4, 6 and 8). Finally, compressed air at 82 bar pressure and about 50°C is stored in an underground cavern.

Water is used for cooling the compressed air. During the compression stage water circulates through the heat exchangers (2, 4, 6 and 8) and reduces the temperature of the air. Heated water is used to charge a thermal storage tank. The supply and return water temperatures from the TS system are assumed to be 40°C and 90°C. The TS tanks are connected to a District Heating network.

During the expansion stage, compressed air is throttled using valve (26), preheated in heat exchanger (21) to about 400°C and delivered to a combustor (22). Natural gas is used for combustion. After the combustor (22) the mixture of compressed air and burned gases enters the first gas turbine (23). Exhaust gas mixture is supplied then to a second combustor (24) where it is heated to about 870°C at 17 bar pressure. Hot gas is delivered to a second gas turbine (25) where it expands. Finally, hot gas, at a temperature of around 430°C after the gas turbines, is used to preheat the incoming compressed air stream in a heat exchanger (21). The temperature of the hot gas stream after the heat exchanger (21) drops to about 75°C. All calculations were performed at constant +15°C (288 K) ambient temperature and 101.3 kPa pressure.

Figure 12: Compressed Air Energy Storage combined with Thermal Storage.

2.4 Economics of heat

To examine the economics of low carbon heating systems, the research *The impact of future heat demand pathways on the economics of low carbon heating systems* (Sansom *et al.*, 2012) was conducted by the UKERC Energy Supply theme. In the first part of the project, a two stage linear regression heat demand model was constructed. The second part examines the economics of low carbon heating systems.

2.4.1 Heat demand modelling

Heat demand forecasts are frequently presented annualised. Although this is helpful for macro-economic analysis, without further refinement it is not possible to determine the assets required to meet short term variations in heat demand. For example, electrification of heat will have a direct impact on peak electricity and the capacity of the assets to meet this demand.

The objective of the project was to construct a model that would synthesise half hourly heat demand from actual data where available. These include temperature, daily gas consumption from DECC (DECC, 2010a) and heat profile data with reconciliation to annual consumption data or demand projections. The demand data can then be used to support the technical and economic evaluation of low carbon heating technologies such as heat pumps and district heat networks. A representation of the model is shown in Figure 13.

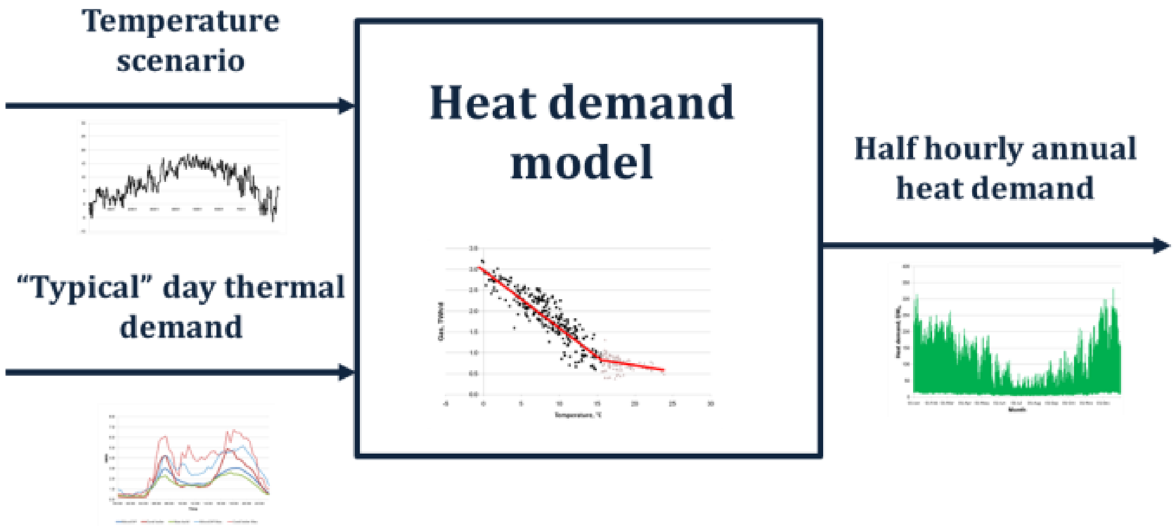


Figure 13: Heat demand model

Figure 14 presents the peak electricity demand for Pathway 3, taken from DECC’s 2050 Pathways report (DECC, 2010b) with assumptions made on installed appliances. This is the electricity demand at the consumer premises, i.e. before distribution and transmission losses. The solid black line shows the peak demand for Normal weather and the blue block is the range from the Mild to Cold temperature scenarios.

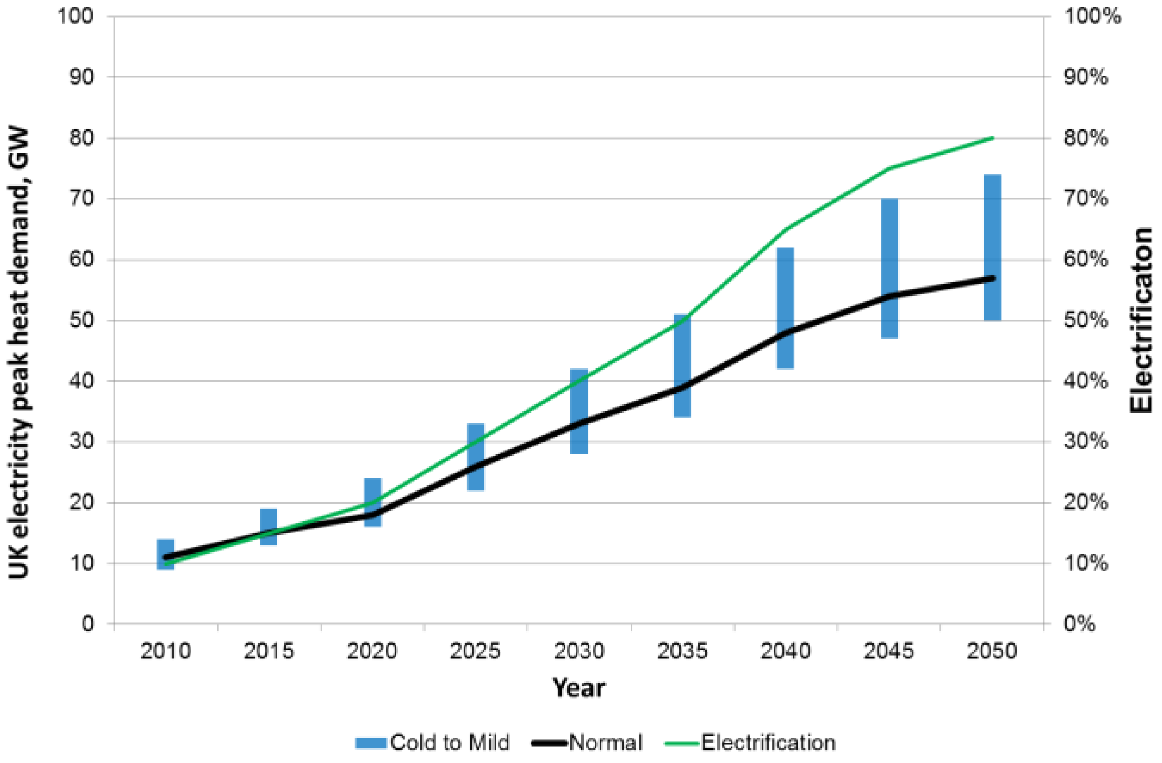


Figure 14: UK electricity peak heat demand at consumer premises for Pathway 3

The results illustrate the increase in sensitivity to electricity demand from changes in temperature. For example, the electricity peak heat demand for Pathway 3 in 2050 is 57 GW for the Normal temperature scenario which would result in a near doubling of electricity peak demand. This will require a significant increase in generation capacity as well as substantial reinforcement of transmission and distribution systems. However, for the cold temperature scenario, electricity peak heat demand is further increased to an estimated 74 GW, nearly 30% higher. To maintain the current level of supply security for heat, mostly provided for by gas, would require additional investment in assets such as peaking plant and/or demand side management arrangements as well as further network reinforcement. Hence, consideration needs to be given to the impact on supply security standards arising from the electrification of heat.

The primary limitation of the heat demand model is the lack of high quality actual data. In contrast to electricity demand where data is readily available, there is not the equivalent for heat. The master demand profiles were created from the only data that was available and, although there were 114 sites, only 71 sites were suitable due to data logger problems. Demand data was also collected over a relatively short period of time and only included a single winter.

Hence the main area for further work is to improve the master demand profiles and to collect the data over a longer period of time so that the impact of temperature, and cold temperatures such as 2010, can be better understood.

2.4.2 Economics of low carbon heating systems

A “high level” economic analysis comparing residential heating systems was undertaken. This compared the continued use of household gas condensing boilers up to 2030 followed by their replacement with household ASHPs (cases 1a and 2a) with district heating (cases 1b and 2b). The study was undertaken for pathways (DECC, 2010b) within two scenarios; a 2030 transition scenario (cases 1a and 1b) and a 2050 targets met scenario (cases 2a and 2b). Peak heat demand is calculated from the heat demand model based on the cold temperature scenario with 33million households in 2030 and 40 million households in 2050.

The analysis showed that district heating has higher levelised costs for all the pathways examined up to 2030. Simplified diagrams of the examined cases are shown in Figure 15.

As heat is fully decarbonised to 2050, district heating has lower costs for all the pathways examined. This is mainly due to the cost of household ASHPs and the additional power plant capacity to meet the demand requirements of the ASHPs. Note that, as expected, the cost of the heat network has a significant adverse impact on the economics up to 2030. However, as condensing gas boilers are replaced with electric heat pumps, heat and electricity network costs have a secondary impact. For example, if the heat network cost were to double and there were no electricity reinforcement costs, district heating would still be marginally more economic than electric heat pumps. This is because the cost of heat pumps and the investment in generation capacity dominate.

The economic analysis has been useful but further, more detailed, analysis is required to enable robust conclusions to be made. For example, demand side action has not been included and this will reduce the peak demand and hence improve the economics.

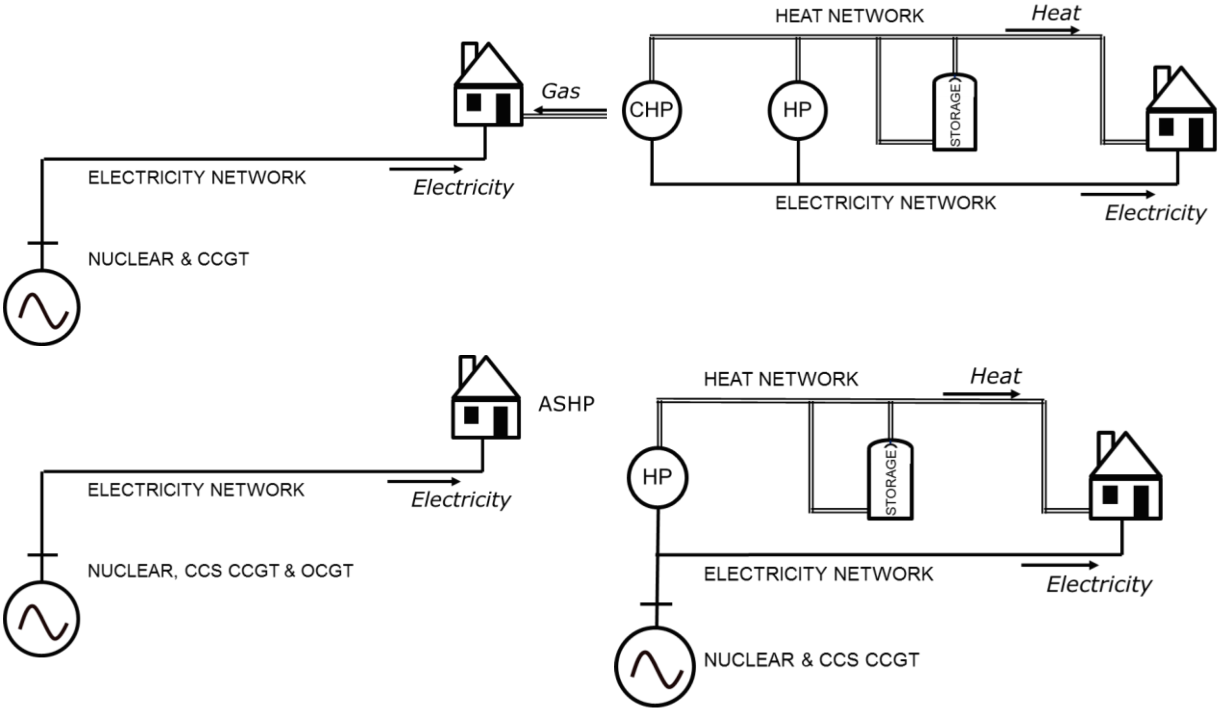


Figure 15: Cases used in the economic analysis; top left – Case 1a, top right – Case 1b, bottom left – Case 2a, bottom right – Case 2b

2.4.3 Combined heat and electricity model

An integrated heat and electricity model has been constructed which incorporates half hourly heat and electricity demand and includes wind, CHP, thermal storage and thermal generating plant. The household heating systems include those connected to the district heat network as well as household heat pumps and electric storage heating systems. Investigations will enable the operational performance to be evaluated as well as other features such as system support from thermal and electricity storage and the management of wind intermittency.

2.5 Research gaps and opportunities

To identify the research gaps and opportunities in the area of heat systems, a two day workshop was held on the 26 and 27 March 2013 in Oxford. The aim of this workshop was to bring together key participants from academia, government, industry and NGOs to identify gaps and opportunities.

The workshop identified research priorities (UKERC, 2013), including:

1. The cost of waste heat?
2. An integrated approach to understanding energy systems and Interdisciplinary research ("...necessary to combine policies, the technical, and the social with the need for the creation of viable business models with application to real world case studies to develop the lowest cost, and optimal systems" (UKERC, 2013))
3. The role of heat in an energy system; balancing, decarbonisation, governance, social aspects, and attitudes from Industry and individuals in homes.
4. Combining uncertainty into models with a combination of different sector models (e.g. industry, domestic, electricity and gas/heat) and consideration of the scale of modelling at EU, national, regional and the individual level of infrastructure.
5. Public attitudes and engagement.
6. The identification of optimum location of power stations for District Heating, Carbon Capture Storage, fuel supply and electricity supply.
7. Future of the gas network; for example, hydrogen injection.
8. Industrial heat; incineration, by energy and waste link ups, heat recovery in general e.g. at power stations and through heat networks and infrastructure.
9. Economic understanding of the value, to society, that industrial heat delivers and a system perspective for whole community energy demand and resources.

Finally, the research areas and questions identified in the Low carbon heat section are summarised in Table 8.

Table 8: Research areas and research questions identified in the Low carbon heat section of this report

Section	Identified Research Areas and Questions:
Heat Pumps	- How does control strategy of heat pumps affect the electricity network? - How can load shifting strategy be applied to reduce the peaks resulting from the operation of heat pumps? - What is the role, if any, of smart meters in smoothing the impact of heat pumps? - What is the effect of load shifting on the room temperature and how it could affect customers' satisfaction? - How does human behaviour affect the operation of heat pumps? - What is the impact of heat pumps on electricity infrastructure due different hot water consumption patterns in well insulated buildings? - What is the role of thermal storage in heat pump systems? - Where are the most promising niches for heat pumps within the existing housing stock? - What percentage of the national housing stock would be technically suitable for heat pump installation, now and in the future? - How can low temperature heating systems be installed in existing homes at least cost and with least disruption? - What is the risk that mass installation of heat pumps would increase the summer cooling demand? - What are householder experiences of heat pumps, particular when retrofitted into older homes? - How can a small-scale and fragmented heat pump installer industry transform into a sector capable of delivering high quality installations in large numbers?
Micro CHP	- The operation of micro-CHP at building level - The impact of micro-CHP systems on electricity networks. - Development of small smart energy networks using micro-CHP and other low carbon heating technologies.

	- Development of biomass micro-CHP technologies - The role of energy networks with thermal storage and CHP in demand-supply balancing.
Community CHP Systems	- Further development of simplified exergy and exergoeconomic analysis methods for use by energy systems planners and designers. - Investigation of direct or indirect use of biomass in gas turbines. - Development of medium and large scale smart community energy systems.
District Heating	- Further development of DHN optimisation methods for large networks consisting of branches and loops is needed. - Investigation on variations of heat demand and its effect on the operation and design of DHN taking into account the occupancy type, consumer behaviour, diversity factor and outside temperature variations are required. - In a DH, network pumps are sized to overcome pressure loss along the route with maximum pressure drop. Branches or pipe sections located closer to the heat source experience a much higher differential pressure. Therefore, pipe diameters of these branches can be reduced further to match the differential pressure available at the branch connection to the main pipeline point. Consequently, the capital investment and heat losses of the DH pipe network decrease. Analysis of how the design of DHN using variable pressure losses for pipe selection can improve economics of DHN is needed.
Multi-vector community energy supply systems	Requirement for a consistent approach for estimating a projection of the marginal emissions factor for grid supplied electricity
Energy Storage	Further investigation of CAES-TS systems.
Heat demand modelling	Measurement of high quality heat demand data.

3. Gas and Electricity Networks

Gas and electricity network operation and investment are experiencing a period of uncertainty and sustained change as the UK moves to a decarbonised energy system. Issues such as the integration of offshore renewables, meeting energy decarbonisation and renewable targets, maintaining resilience of energy systems and reorganisation of energy markets are reshaping the investment and operation of energy systems.

The Energy Supply theme focused on five key areas in gas and electricity networks research; the 'smart metering and demand side participation' project investigated the efficacy of electricity demand response for various uses in electricity network operation; the 'energy security, supplies of gas', project explored the impact of the resilience of the energy network and builds upon the network model built during UKERC phase 1; the 'Integration of new generation: control of offshore wind farms' project examined the impact of different wind farm control strategies and offshore network design methodologies; the 'Integration of European electricity markets' project analysed the impacts of greater interconnection between European energy (electricity) systems and the fundamental changes to market arrangements and incentives that may be needed in the future was addressed in the 'electricity market design for a sustainable low-carbon electricity sector' project.

3.1 Smart metering and demand side participation

The GB gas and electricity networks are closely related. At present much of the electricity supply side flexibility is provided by Combined Cycle Gas Turbine (CCGT) gas power stations. The increasing need for electricity generation flexibility will mean that Gas System Operator (GSO) must be increasingly aware of electricity network supply and demand forecasts. Likewise, the National Electricity Transmission System Operator (NETSO) must be aware of the gas network demand, supply and capacity forecasts. How much of a role demand response (both gas and electric) could (and should) play is an open research question. The research described here covers investigations of the efficacy of electricity demand response for various uses in electricity network operation.

Balancing Services: Services defined and procured by National Grid to balance demand and supply and to ensure the security and quality of electricity supply across the GB Transmission System.

Frequency Response: Response to changes in system frequency (the fundamental frequency of the voltage waveform) provided by demand or generators. It is divided into two categories; continuous (for second by second changes) and Non-dynamic (a discrete service triggered by an abnormal frequency deviation – e.g. due to loss of a large generator).

Primary Frequency Response (or Primary Response): A Balancing Service relating to an increase in generation or decrease in demand following a predefined drop in frequency (Non-dynamic Frequency Response). It must operate within 10 seconds of a frequency deviation and persist for at least 30 seconds.

Monte Carlo Simulation: Simulations that use the repeated generation of random numbers.

At present, the National Electricity Transmission System Operator (NETSO) ensures that the system remains stable by defining Balancing Services (including provision for adequate frequency response) and allowing generators or relatively large non-domestic demand to offer to provide them. A barrier for demand side participation in Balancing Services, such as low frequency response, is the lack of access to the mechanism by which the NETSO accepts offers and bids for changes in large generation or demand (to ensure the system remains stable). It would be difficult for the NETSO to make individual agreements with smaller customers for provision of such services. Whether the smart metering system could facilitate access to Balancing Services for smaller customers, via aggregators and appliance manufacturers, remains an open question.

The main ways in which smart metering could facilitate demand side participation in Balancing Services include; co-ordination of demand response (via tariffs or direct control), reporting of availability of response and verification of response (as the NETSO must have evidence that demand response was provided).

An investigation in to the use of Smart Meters to co-ordinate demand response, for frequency response, was undertaken (Samarakoon *et al.*, 2011a). In the study domestic loads were divided into five control group categories, based on their characteristics (**Error! Reference source not found.**16). A load control algorithm was presented where, when the frequency dropped, loads were switched off at different frequencies. The loads were then switched back after at a randomised time delay. The paper concluded that, for a possible future GB network with a system inertia of 9 seconds and an anticipated maximum generation loss of 1800MW, 1000MW of controllable load would be required to provide adequate low frequency response.

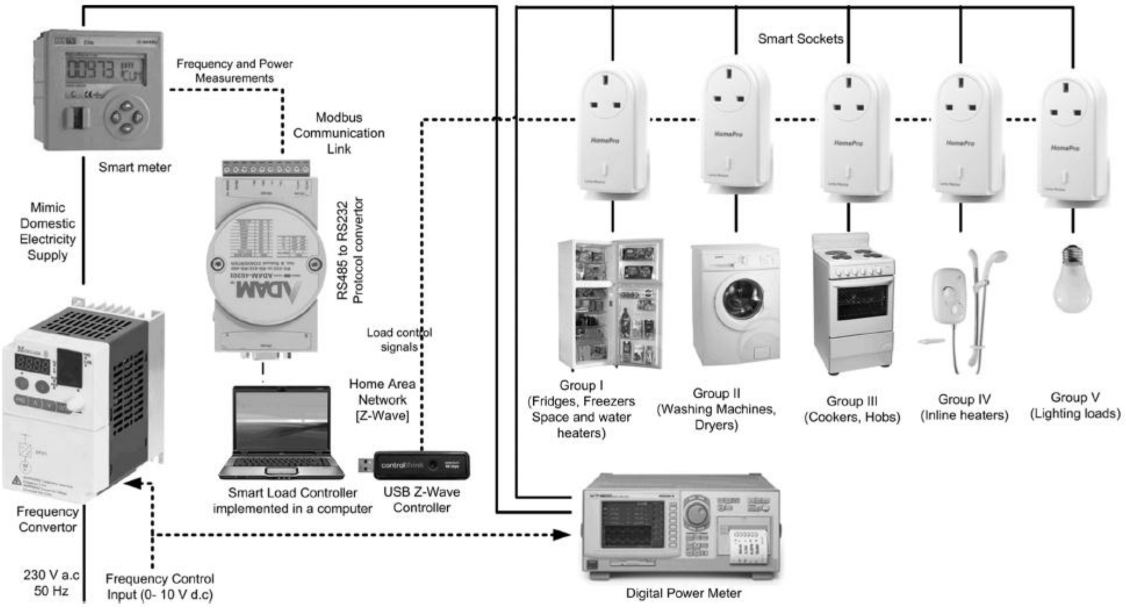


Figure 16: Layout of the experimental load control scheme (appliances were represented by lamps) (Samarakoon *et al.*, 2011a)

An analysis of the communication requirements (number of messages and timescale) for reporting the availability of demand response using smart meters was undertaken (Samarakoon *et al.*, 2013). A scheme was presented to minimise the communication requirement of continuous demand reporting by using data concentrators, arranged hierarchically, at distribution substations (Figure **17**: 17). The paper notes that the impact on the Wide Area Network (WAN) can be reduced by sending messages only when the demand changes significantly and by aggregating the measurements using concentrators.

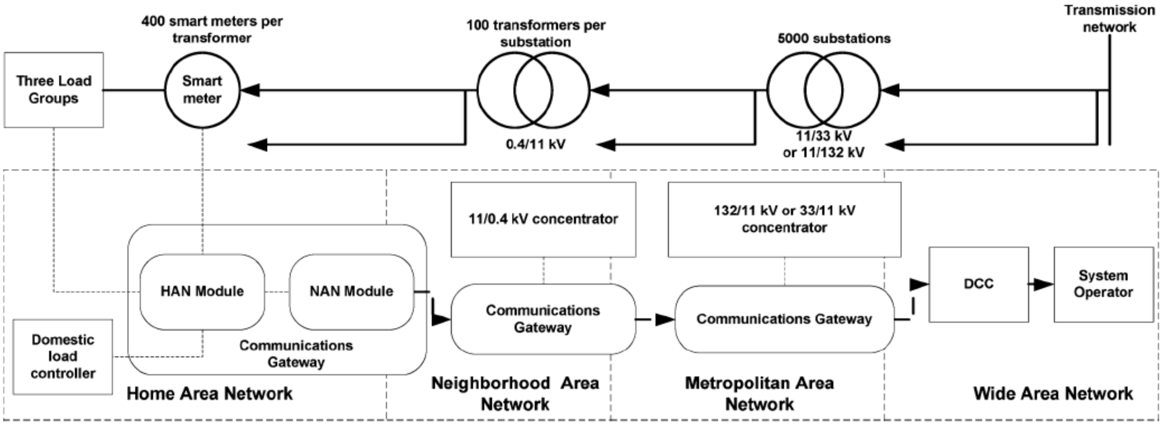


Figure 17: The Communication network and concentrator layout (Samarakoon *et al.*, 2013)

The use of smart meters to verify that Frequency Response has occurred, and therefore provide a basis on which to distribute rewards was investigated (Thomas *et al.*, 2012a). Firstly, a scheme to enable system operators to be aware of frequency response capability was put forward (See Figure 18). After this, a scheme to allow system operators to verify the operation of frequency responsive devices using smart meters was shown (Using refrigerators to provide Primary Frequency Response has been investigated (Cheng *et al.*, 2013). The research involved modelling the variation of temperature within refrigerators, assigning priority levels to refrigerators and building a simplified model of the GB power system. A population of 1000 fridges was modelled with variables determined through Monte-Carlo simulation. The output was scaled to represent all refrigerators in Britain. The simulation results, shown graphically in (Cheng *et al.*, 2013), imply a Primary Frequency Response of approximately 150MW based on a sudden generation loss of 1320MW (25GW base load).

In further work, the use of Bitumen heating tanks for Primary Frequency Response was studied and compared with the response from a population of refrigerators. The work is also looking at how the NETSO can estimate the frequency response availability based on a known population of bitumen tanks and refrigerators. This work is ongoing.

A study of UK flexible domestic load predicted that electric space and water heating and cold and wet appliances demand will increase from 48TWh to 62TWh in 2030, mainly due to an increase in electric space and water heating (Drysdale *et al.*, 2013). Trends within appliance categories were projected until 2030 (see Figure 19). The projections within each category were ascertained by estimating future trends for constituent appliances within each category (Figure 19:). The paper highlights the need to recognise behavioural aspects of energy consumption when considering access to demand response.

Figure 18: Smart meter based algorithm for detection and recording of frequency response for verification by the system operator. $P_{t=0s}$ = demand when frequency deviation detected. $P_{t=2s}$ = demand 2 seconds after frequency deviation detected

. An example scheme was studied, where the operation of 20% of domestic washing machines was paused at 1830 hours on a weekday. An estimated 135MW total Primary Frequency Response was provided by 291,778 washing machines (1.12% of households).

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Table 9: Steps for system operators to become aware of connected Frequency Response capability (Thomas *et al.*, 2012a).

No.	Step	Description

1	**Specification**	System Operator specifies desired frequency response characteristics for frequency responsive devices.
2	**Manufacture**	Manufacturers incorporate frequency response into appliance power supplies.
3	**Testing and Certification**	System Operator tests and certifies appliance frequency response characteristics.
4	**Registration**	Customers purchase, register and connect appliances.
5	**Calculation**	System Operator calculates availability of distributed frequency response based on number of registered devices and device usage patterns.

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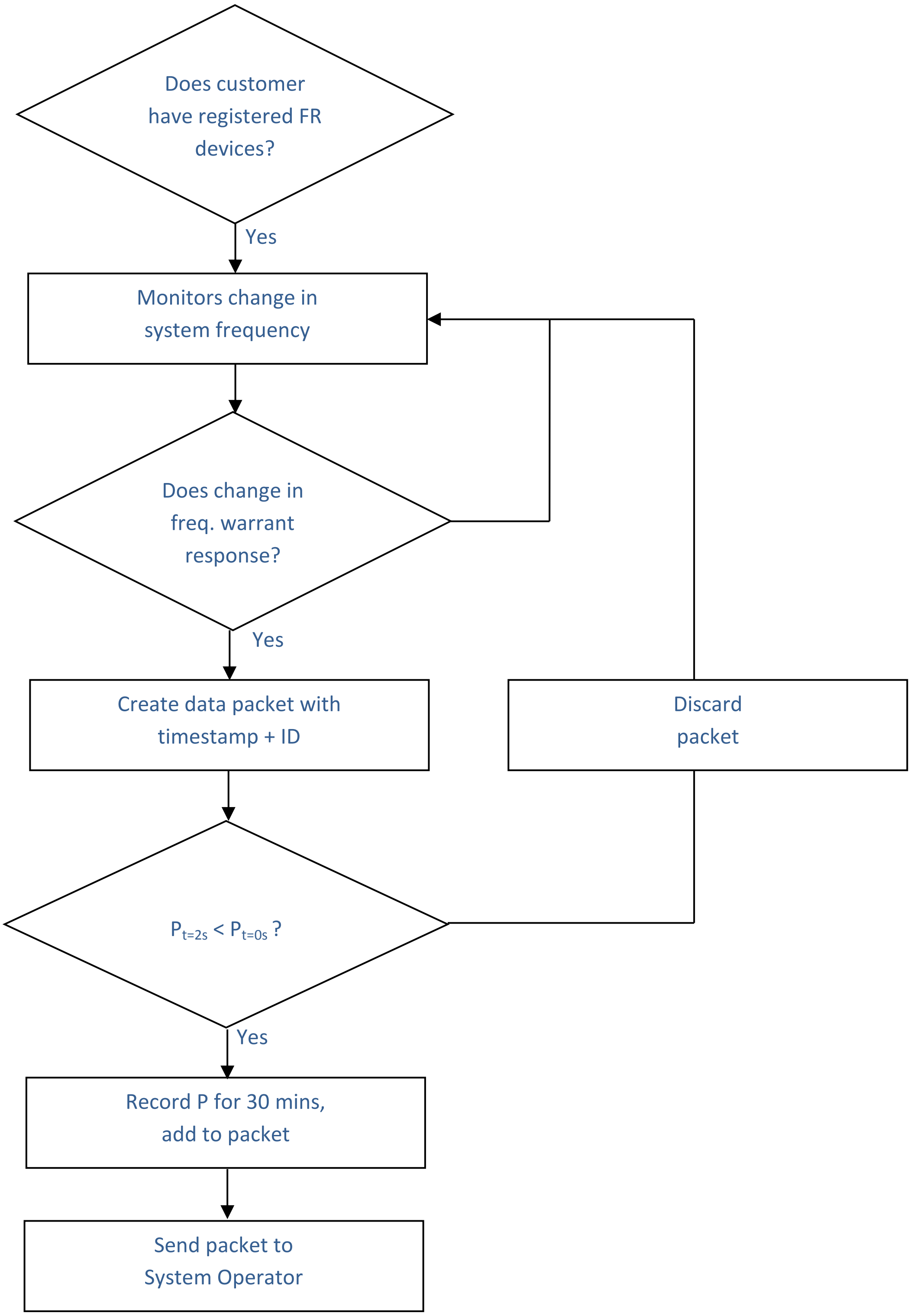

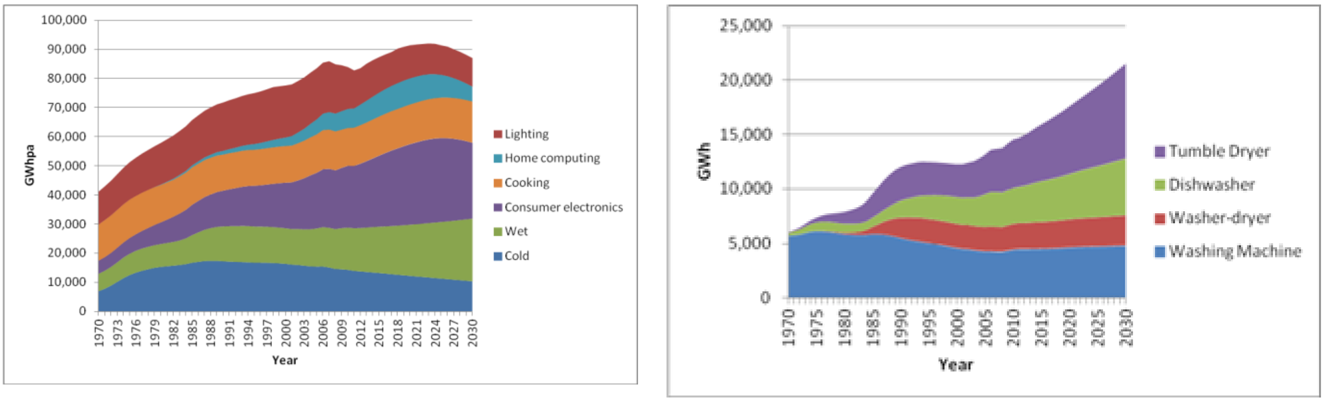

Figure 19: Left- UK total domestic appliance consumption 1970 – 2030 (projected). Right- UK domestic wet appliances demand 1970 – 2030 (projected) (Drysdale *et al.*, 2013)

A technique for providing demand response using domestic smart appliances, based on an existing hourly electricity price signal, was presented (Nistor *et al.*, 2011). In the scheme, customers set a required finish time for washing machines, dish washers and tumble dryers. The devices then look at the expected hourly prices for the devices and optimise the operation of the device accordingly (aiming for minimum cost). It was concluded that more granular tariffs (i.e. half hourly), with a higher ratio between peak and off-peak prices, must be used to improve the benefit of the scheme. The GB smart metering roll out will include half hourly tariffs (DECC, 2012e).

Following this, research examining the capability of domestic smart appliances to provide reserve services was done (Nistor *et al.*, 2013a). The work investigated the use of smart appliances to contribute to National Grid's STOR (Short Term Operating Reserve) Balancing Service. It was found that, with a 20% penetration of smart appliances, the demand response can provide up to 54% of the operating reserve requirements of the GB power system depending on the time of day.

Short Term Operating Reserve (STOR): A balancing service for the provision of additional active power from generation and/or demand reduction.

Investigation of adding network constraint related constraints to price based smart appliance control schemes, to ease distribution network thermal overloads, has been undertaken (Nistor *et al.*, 2013b). Whilst it was found that this reduced the cost saving (through not taking full advantage of price variation) for the end users, it did remove thermal overloading of the local transformer for the example system.

The amount of distributed generation that can be connected to the distribution network is limited by voltage constraints (Bollen *et al.*, 2011) (as well as other constraints such as thermal limits, fault level and anti-islanding stability protection). Investigation of whether smart metering can be used to aid voltage control schemes, and therefore improve the hosting capacity of distributed generation, is ongoing.

A Smart metering system test rig has been developed (Burchill *et al.*, 2012). This consists of four smart meters, communication links via GPRS and an electricity network modelling tool – a Real Time Digital Simulator (RTDS) (**Error! Reference source not found.**). This is presently being used to investigate improvement of a distribution transformer tap change control algorithm. The test rig is also being used to investigate the detection and mitigation of cyber-attacks targeting smart meters and their associated infrastructure.

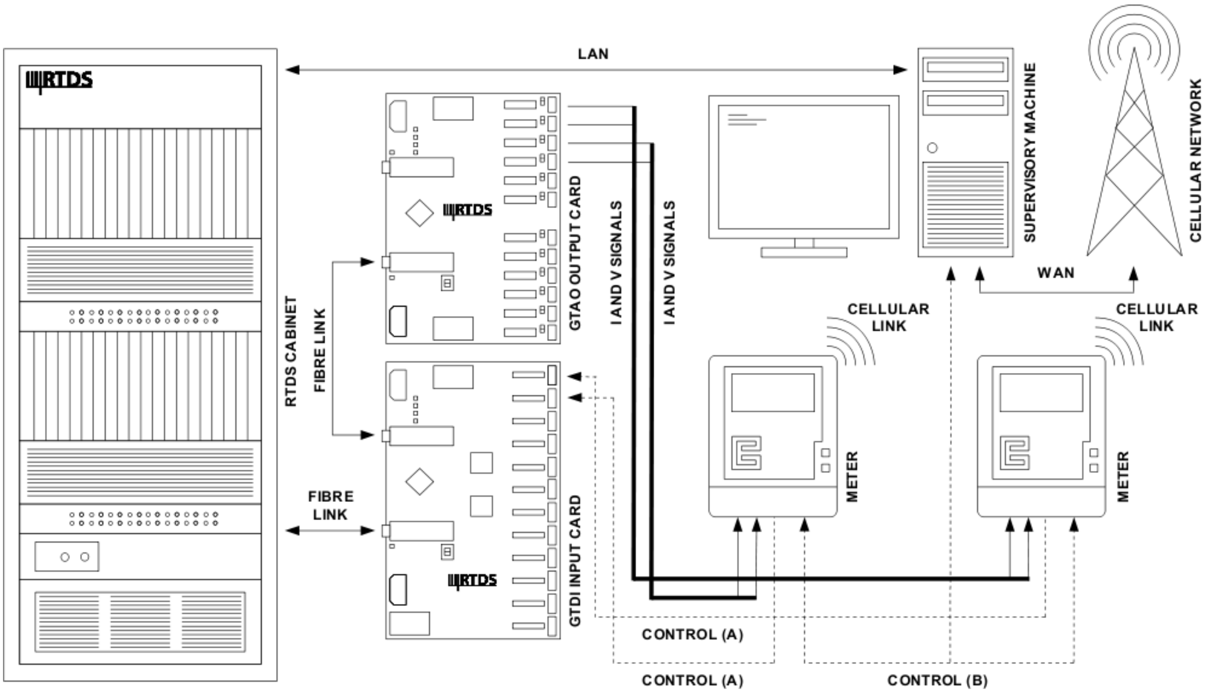

Figure 20: Combined Smart Metering, Electricity Distribution Network and Communication System Test Rig (Burchill *et al.*, 2012)

Knowing the state (voltages and voltage angles at all points, and power flows between busbars) of a distribution network enables the Distribution Network Operator to manage constraints (e.g. equipment thermal ratings, insulation limits).

It was found that the state can be estimated using the previous day's half hourly usage data, supplemented by relatively few real-time measurements within the distribution network (Samarakoon *et al.*, 2011b). The investigation of distribution system state estimation algorithms is an active research area.

3.1.1 Research Gaps and Opportunities

The increasing integration of gas and electricity network presents numerous research challenges. New automated data and information flows, between the main actors operating and planning the gas and electricity networks, are expected to be established over the coming decades. As the fringes of the networks are largely devoid of automated data collection, the GB smart metering system represents a significant change. Increased localised active control of network components will lead to an amount of decentralisation of control. Questions remain around the potential for adverse complex control interactions for highly decentralised systems.

Research areas were identified in the Hubnet position paper series (Thomas *et al.*, 2012b; 2013). The identified areas included:

- Complex control interactions
- Distribution Network Modelling
- Multi-timeframe, multi-objective models
- Demand modelling
- Demand response efficacy, operation and verification
- Control of network power flows
- Demand side Frequency Response
- Visualisation and decision support
- Microgrids and Islanding
- Cyber Security
- Energy use reduction
- State estimation
- Standards and guidelines
- Load disaggregation
- Protection Systems
- Governance

Some of the key questions raised, relating to whole systems / multidisciplinary research, include:

Is the present regulatory structure of the GB system adequate and how, if at all, it should be changed?

"Notably, the IET's Power Network Joint Vision (PNJV) position statement (IET, 2013) recommended that a System Architect role be created. The statement highlighted that, 'Since privatisation in 1990, no single party has had the responsibility to ensure overall systems integration'."

Are customers are prepared to accept a lower security of supply in exchange for a lower cost?

"Electricity North West's Capacity to Customers Low Carbon Network Fund project is trialling adding more capacity to the network by removing redundancy (ENA, 2013). Smart metering will allow for customer's continuity of supply to be monitored – therefore opening up potential for negotiation over security of supply versus infrastructure upgrade. It is probable that regulatory changes, not to mention a change in society's expectation of the power system, would be required for this to happen."

What is the efficacy of domestic and non-domestic demand response?

Much of the UKERC research mentioned in this section begins to address this question. Proving the efficacy of automated demand response involves; detailed modelling of demand (including EVs and HPs) and generation, prediction of consumer uptake, fitting to existing or proposed regulatory structures. Numerous approaches exist; completely autonomous (e.g. frequency based), price signal based control or centralised control.

Which parties should have control of demand response and how should it be regulated?

"Conflict could arise where different parties want to use demand response tariffs to move demand in opposite directions (e.g. wind generators wishing to encourage demand during high wind and DNOs wishing to limit it due to local constraints)."

What control philosophies should be adopted? How much automation should be adopted?

As the number of different controls on the power system grows, the risk of unforeseen, and potentially damaging, interaction of controllers grows. The creation of a software and/or hardware platforms on which to test proposed new controllers and overall control schemes will become important.

How can whole system models be improved to better inform engineers in both operation and planning?

Creating models with which new control methods can be tested (with confidence of the results) remains a challenge. The complexity of the power and gas systems across all timeframes (e.g. transient to seasonal) must be encapsulated, whilst minimising computational burden.

How can engineers be prevented from "getting lost trawling though data"?

Osborne *et al*. (2012) raise concern that engineers "will get lost trawling through data" as a result of increased volumes of data being collected. They go on to say that a range of visualisation and decision support tools are required to prevent engineers becoming overwhelmed. What information must be communicated, and when it should be delivered, are fundamental questions. The closely related question of how the information should be presented is also important.

How can the power network hosting capacity for heat pumps, electric vehicles and renewable generation be increased?

Accurate modelling of EV, HP and DG usage patterns is important to test network limitations. A more closely controlled distribution network will mean that a more finely modelled network is required in order to validate control schemes.

3.2 Energy Security, Supplies of Gas

Domestic gas production in the UK has been declining at a significant rate with current forecasts predicting a reliance on imports for 70% of its gas supplies by 2020 (National Grid, 2011a). Over the next decade, a number of coal and nuclear power plants are set to retire (National Grid, 2011b). This trend has already led to numerous infrastructure developments such as new power plants, electricity transmission lines, gas pipelines, Liquefied Natural Gas (LNG) terminals, and gas storage facilities.

The decisions regarding the magnitude, and appropriate time of incorporating new infrastructure in future systems to satisfy energy demand will depend on many factors, including ensuring that any new developments are economic, environmentally sound and provide adequate security of supply.

With a large share of gas based electricity generation, the electricity and gas sectors in the UK will continue to become significantly more interlinked. Given this increasing interdependence, an integrated approach to the analysis is desirable to assess common issues such as economics and the security performance of the future UK energy system under various energy scenarios.

The focus of the project ‘Energy Security, Supplies of Gas’ was to update the CGEN (Combined Gas and Electricity Network) model (Chaudry *et al.*, 2008) to address issues surrounding energy security and investigate the virtues of an integrated approach to energy infrastructure planning.

Work was carried out on the development of a power generation expansion module that upgrades the CGEN model (endogenous power generation expansion). This will allow questions regarding the future generation mix in GB to be addressed.

Additionally the CGEN model was upgraded with Monte Carlo analysis capabilities. This allowed the model to assess impact on reliability of the energy system (LOLP, EEU etc.) due to a multitude of energy uncertainties such as varying levels of generation capacity margin, supply availability and demand.

Project objective 1: *Upgrading the CGEN model – Power generation expansion module*

The objective of this work was to upgrade the CGEN model to allow expansion of power generation capacity over a planning time horizon. This upgrade greatly increased the technical capabilities of the CGEN model (CGEN is now capable of analysing power generation expansion without the need for data from other models). In addition to this upgrade CO_2 pipe infrastructure costs for implementation of CCS and hydrogen electrolysers were modelled within CGEN.

The CGEN model is comprised of different components. The focus of the modelling is on power generation expansion, gas and electricity transmission network expansion, gas storage, gas interconnector and LNG supplies. CCS-equipped generating units are modelled in CGEN through consideration of the additional capital and operational costs of CCS technologies. These units are assumed to be located in the vicinity of the sequestration sites and therefore no additional CO_2 transmission infrastructure is assumed.

Different parts of the infrastructure are arranged into distinct categories, describing energy supply, energy transportation (networks), generation technologies, and end energy use. The flow diagram considered in CGEN is shown in Figure 21.

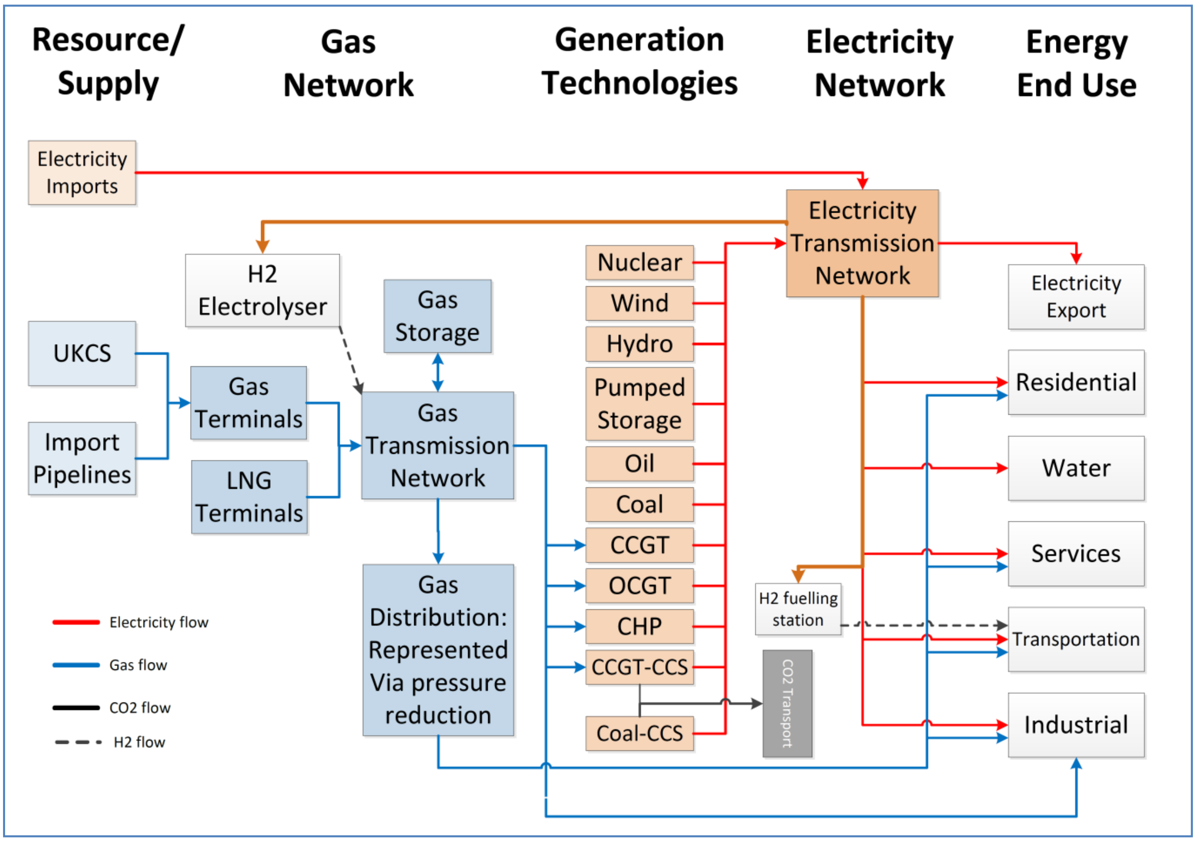

Figure 21: Flow diagram considered in CGEN

Resource/supply

This includes bounds (user defined maximum/minimum values applied across operational and planning time steps), such as level of a gas field (bcm) and maximum gas production capacity (million cubic metres, mcm/day), or availability of primary energy supplies (gas, coal, oil etc.) and electricity imports. Gas import interconnectors are modelled as gas pipes with maximum transport capacities.

Networks

The gas network includes the detailed modelling of high pressure transmission pipelines, compressors, gas terminals/interconnections and storage facilities (including salt cavern, depleted reservoir and LNG). The gas flow in a pipe was determined by employing the Panhandle 'A' equation that calculates the gas flow rate given the pressure difference between upstream and downstream nodes (Chaudry *et al.*, 2008).

A DC power flow model was used to represent a simplified high voltage electricity transmission network. The DC power flow formulation enables the calculation of MW power flows in each individual transmission circuit.

Gas turbine generators provide the link between gas and electricity networks. They are considered as energy converters between these two networks. For the gas network, the gas turbine was looked upon as a gas load. The value of the gas load depends on the electrical power flow from the generator. In the electricity network, the gas turbine generator is a source.

Generation technologies

CGEN includes models for all the conventional generation technologies such as CCGT, Coal, and Nuclear. Generation technologies are described by a number of characteristics such as maximum generation and thermal efficiencies.

Renewables such as wind and wave power generation are usually represented by using stochastic models. Use of stochastic modelling would drastically increase simulation solution runtime and therefore an alternative method of using average load factors that capture regional variations of the UK renewables resource was used. Average load factors reduce the maximum possible generation from unconventional/renewable plants and are used to capture the variability of generation output.

The decisions on type, capacity, location and time that new generators need to be added to the system are addressed by a generation expansion module and by taking into account techno-economic parameters such as capital and operational costs, fuel price, service lifetime and CO_2 emissions.

End energy use

Gas and electricity energy demand for five distinct sectors was assumed in CGEN (residential, services, industry, transport and water sector). Gas used for electricity generation is calculated endogenously within the model.

The objective function of the CGEN model is comprised of investment costs of new infrastructure and operational costs of the system. At each planning time step, CGEN decides upon the expansion of the gas and electricity infrastructure.

For both gas and electricity networks, CGEN adds transmission capacity to satisfy peak demand requirements. Figure 22: illustrates how the optimisation routine within CGEN explores all possible solutions to satisfy peak demand. This ranges from building additional network capacity to the re-dispatching of energy (e.g. substituting cheaper gas from Scotland with expensive gas from LNG terminals in the south of England in order to bypass transmission bottlenecks); the model will select the cheapest solution over the entire time horizon.

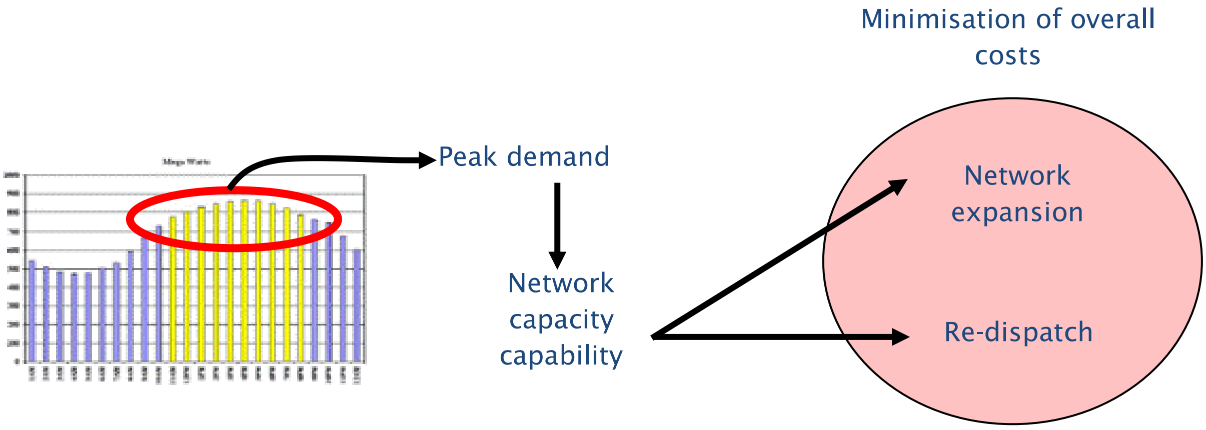

Figure 22: Network infrastructure expansion

Gas network planning and operation model

The gas network assets that are reinforced in the model over the planning period are gas pipes, compressor capability, LNG terminal capacity, import pipeline capacity, and gas storage facilities. Gas network planning optimisation will simultaneously satisfy operational and planning constraints. Detailed formulation for gas network planning and operation can be found in Chaudry *et al.*, 2014.

Power system planning and operation model

Power generation and transmission network expansions take place through adding new generators at each busbar and increasing transmission capacity between buses, respectively. DC power flow equations were used to analyse the electricity network. Detailed formulation for power system planning and operation can be found in Chaudry *et al.*, 2014.

The CGEN model was used to determine the gas and electricity network capable of meeting varying demand and power generation profiles for two distinct scenarios. These two scenarios illustrated a do nothing (reference) and low carbon future.

Table 10 summarises the gas infrastructure investment selected by CGEN under the two scenarios from year 2015- 2030:

Table 10: Summary of CGEN gas supply infrastructure expansion 2015-2030

Scenarios	Reference	Low-Carbon
Interconnectors	No additional	No additional
LNG terminals	160 mcm/d	160 mcm/d
Gas storage	2000 mcm	1000 mcm

The scenarios showed that new gas interconnectors were not selected by CGEN but there was considerable investment in new LNG terminals to compensate for declining domestic gas supplies. This was largely driven by assumptions about the relative cost of continental gas and gas available through LNG markets. Additional gas storage is selected in both the reference (REF) and low carbon (LC) scenarios.

The network for each scenario can be summarised as follows

Reference (REF):

- Coal and gas dominate generation capacity mix by 2030
- Gas demand from power and residential sectors remains strong over the time horizon
- High gas demand leads to lower domestic gas reserves than other scenarios by the end of 2030

- This scenarios leads to more gas infrastructure being commissioned to meet demand (mainly LNG terminals and gas storage facilities)

Low Carbon (LC):

- The low carbon targets of 80% reduction by 2050 (~26% by 2020) results in an increase in cleaner technologies such as coal CCS and wind. Gas still maintains a large generation capacity, albeit at lower load factors.
- Gas used in the residential and industrial sector from 2005 to 2030 has remained largely constant.
- Domestic reserves at the end of 2030 are similar to the reference scenario.
- LNG gas terminals and gas storage facilities are built to meet demand from mainly the residential and industrial sectors

Both scenarios suggest that gas will continue to play an important role in meeting climate change targets and provide energy security. Gas will remain a vital component in electricity generation in the short term as a bridge to a low carbon generation mix and then as a flexible and diverse supply of energy for balancing supply and demand.

The results indicate the degree to which GB will become import dependant. The broad pattern across all the scenarios is that LNG capacity substitutes for UK domestic production and, in the 2020s, for Norwegian imports.

The output of CGEN demonstrated the capability of the model to perform simultaneous expansion planning of a large system such as the GB gas and electricity network. The integrated nature of CGEN allowed analysis of investing in either gas or electricity networks in order to satisfy demand at lowest cost.

Project objective 2: *Monte Carlo CGEN analysis*

Debates on reliability of energy systems frequently centre on the various drivers of security such as the level of spare capacity (capacity margin) and diversity of energy supplies. The appropriate level of reliability for an energy system is often based on a value judgement of what policy makers, system and market operators perceive to be suitable based on historical values and the likelihood of future scenarios (e.g. growth in renewables; increase in fuel imports etc.).

Increasing importance is being placed on the ability of an energy system to deliver reliable energy supplies to end users (through transmission/distribution networks) and on the inputs to an energy system (i.e. diversity of energy supplies; source/origin of energy supplies; intermittent supplies etc.). There are numerous quantitative measures of energy security and reliability, the focus of such numerical values is to help develop insights into the drivers of energy security and reliability.

A combined gas and electricity network (CGEN) Monte Carlo model was developed (Chaudry *et al.*, 2013). The model integrates the gas and electricity network into a single sequential Monte Carlo framework. Within each Monte Carlo iteration the combined costs of the gas and electricity network are minimised these include gas supplies, gas storage operation and electricity generation. The Monte Carlo simulation calculates reliability indices such as Loss of Load Probability (LOLP) and Expected Energy Unserved (EEU) for the combined gas and electricity network (the cost of EEU is calculated by multiplying the EEU with the value of lost load–VOLL).

The developed CGEN Monte Carlo model can be used to quantify the impact on reliability of the GB gas and electricity infrastructure given uncertainties such as wind variability, gas supply availability and outages to network assets.

Monte Carlo simulation models: are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results; typically one runs simulations many times over in order to obtain the distribution of an unknown probabilistic entity.

An optimisation model (such as CGEN) can be embedded within a Monte Carlo simulation. Therefore, at each Monte Carlo iteration, a set of optimal outputs (dependant on the selection of random model inputs) are produced. This is repeated numerous times to produce the various outputs distributions (e.g. power generation and gas supply probability distributions etc.).

Loss Of Load Probability (LOLP): is a probabilistic weighted average value that measures the likelihood of loss of load. It does not capture the amount of load that will need to be shed. During the period when the vertically integrated CEGB (former nationalised owner of England and Wales generation and electricity network) operated the electricity system a LOLP of at least 0.09 was considered acceptable.

Expected Energy Unserved (EEU): The EEU for any particular period (day, week, year etc.) gives the probability weighted magnitude of interruption to energy supplies (loss of load).

Value of lost load (VOLL): VOLL is the estimated amount that customers receiving energy would be willing to pay to avoid a disruption in their electricity service.

Analysis was performed over a typical midwinter week on a hypothesised GB gas and electricity network in 2020 that meets European renewable energy targets. The efficacy of doubling GB gas storage capacity on the reliability of the energy system was assessed.

Table 11 shows the combined gas and electricity network reliability indices for the reference (current levels of storage capacity) and doubling of gas storage scenario. The LOLP values determined for both scenarios illustrates that the doubling of gas storage capacity has a mitigating effect on the risk of interruptions in the gas and electricity system. When compared with CEGB standards both LOLP values are larger

(CEGB LOLP <= 0.09) but in these scenarios the caveats are; firstly, both gas and electricity systems are considered (only the electricity system was considered by the CEGB); secondly a typical midwinter week was analysed unlike annual values that the CEGB took into account. This would skew the results towards lower values of LOLP; and thirdly, greater levels of wind generation and reliance on gas imports will impact the results (the system used by the CEGB had very low levels of wind generation capacity and gas imports).

Table 11: Reliability indices for the combined gas and electricity network (both scenarios)

	Reference scenario	Gas storage scenario
LOLP	0.18	0.13
EEU (GWh)	1441.9	1237.8
EEU cost (£ bn)	6.5	5.6

The doubling of gas storage capacity leads to a reduction in EEU when compared with the reference scenario. An EEU value of approximately 1-2GWh seems to agree with studies from the UK Low Carbon Transition Plan (DECC, 2011b). The caveats are that this study is for a midwinter week (not annual), both networks are investigated in an integrated approach and that detailed models of the gas and electricity networks are analysed.

The difference between the EEU cost of both scenarios is £900 million (using VOLL figures from (Skea *et al.*, 2011; Chaudry *et al.*, 2011). This number could be used to evaluate the economic attractiveness of investing in greater gas storage or other facilities.

The results suggest that greater capacity margins (in this case gas storage capacity, but also assets such as flexible back up generation) have a positive effect on the reliability of energy supplies. But alas the question is one of economics, is the extra capacity justified given that these assets will have low load factors? This essentially is an issue of balancing the cost of interruptions (societal effects) with the cost of capital infrastructure and operation of the networks.

The results showed the value of analysing the reliability of interdependent energy vectors in a single probabilistic framework. The gas storage scenario showed a general increase in reliability of the energy system under consideration (gas and electricity network) through the availability of fuel for gas fired generators.

Multi-energy vector computation of indices such as LOLP and EEU allows quantification and establishment of metrics that could be used to inform policy makers and system operators on optimum actions to take on investment (gas vs. electricity) and provide insights on emerging security/reliability issues (e.g. impact of large amounts of wind generation on multiple energy vectors).

3.2.1 Research gaps and opportunities

Numerous future energy scenarios (DECC, CCC) favour a ‘balanced transition’ in the provision for energy infrastructure, where the electricity, gas and heat networks all play a part in the cost effective path to meet the 2050 carbon target. Interactions between these different energy sectors are increasing through the wide use of technologies such as CCGT (combined cycle gas turbines), CHP (combined heat and power), heat pumps, circulation pumps, and through the trigeneration of electricity, heat and cooling. Coordinated planning and operation of these technologies and the associated infrastructures will be required to meet the energy demand while maximising reliability and sustainability, and minimising cost.

The integration of multi-vector energy systems has the potential to:

- facilitate larger penetration of low carbon technologies
- provide balancing, storage and congestion relief services for managing the electricity network operation
- improve energy system reliability and resilience
- improve whole energy system efficiency
- maintain future use of incumbent energy networks (e.g. gas network)

The interactions and dependencies between multi-vector energy systems are complicated and yet, there is a lack of research in this board area.

Furthermore, issues regarding the future of gas network and the possibility of whether to decommission parts of the network are compelling research questions (technical, economic and social impacts). Further integration within European energy systems (both gas and electricity) is a research area that merits further work as regulators and systems operators attempt to operate and build efficient networks for balancing supply with demand.

Two possible projects are described in detail:

Resilience of integrated energy systems

The UK Energy White Paper 2011 reaffirmed the three pillars of energy policy as accelerating the deployment of affordable, secure and low carbon energy systems. Energy security is a topic of particular concern in the UK. Typical questions range from whether a low carbon future can maintain or even enhance energy security to if intermittent renewable generation can be adequately backed-up by traditional generators such as combined cycle gas turbines (CCGT) and at what cost. The reliability of energy transmission is of paramount importance to delivering a secure energy system. This requires analysis of issues related to the availability of gas supplies, wind variability and reliability of the supply infrastructure which includes the gas (terminals, pipes, gas storage facilities) and electricity networks. Studies assessing the security and reliability of multi vector energy systems are not common in the literature. Those that do exist do not explicitly model energy infrastructure such as the gas and electricity networks in detail. Given that the interdependency between energy vectors is increasing and that any one energy vector could adversely affect the capability of another emphasises the need for greater understanding of reliability/security of integrated energy systems.

The aim is to investigate the reliability of integrated energy systems. This potential research will deliver insights into the interdependencies between energy vectors and their relationship with respect to security of energy supplies. Various future energy system scenarios will be used to calculate reliability indices such as LOLP (Loss of Load Probability) and EEU (Expected Energy Unserved). Scenarios will assess impact of altering variables such as capacity margins, interconnection, storage capacity and demand on reliability indices. This research also will build on the UKERC project on geopolitics of global gas security that provided a framework for analysis of the different dimensions of gas security.

This potential research will use an integrated energy system Monte Carlo based model to evaluate reliability indices. Modelling will include assessment of risks associated with uncertainties in future fuel prices, fuel supply, carbon prices, energy demand (response) and shocks to the energy system. Furthermore, various future energy system scenarios will be investigated from electricity dominated (with interconnection) to fully integrated (gas/heat/electricity) systems. The model developed will offer geographic scale and time resolution to capture various demand peaks. The Monte Carlo simulation will be based on minimising overall energy costs (optimisation) at each iteration.

There are numerous energy system scenarios depicting how the UK can meet its carbon and renewable targets but far less consideration has been given to if these scenarios are able to meet demand during events such as outages to infrastructure assets and lack of fuel supplies. Therefore the key output of this potential project will be to offer reliability analysis for a number of future system scenarios across a number of energy uncertainties. Multi-energy vector computation of indices such as LOLP and EEU will allow quantification and establishment of metrics that could be used to facilitate decision-making for policy makers and system operators on optimum actions to take on investment (gas vs. electricity) and provide insights on emerging security/reliability issues (e.g. impact of large amounts of wind generation on multiple energy vectors).

The role of gas in the UK energy system

Natural gas has played a key role in the UK energy mix over past few decades. We move into an era where carbon emissions, security and affordability are key drivers that will shape the future energy mix. The question is what role will gas play? Will it simply play a transitional role and be phased out as renewable and low carbon technologies increasingly become more attractive or will shale gas (fracking) help maintain the status quo? What if certain technologies that we count on for carbon emission reductions do not deliver as expected? Do we have a plan B or C? Additionally what do we do with the extensive gas transmission and distribution assets if we were to move away from gas as fuel source?

The key aim of this potential project is to explore the future of gas including the transmission and distribution assets in the UK over the medium and long term. One objective is to examine energy scenarios where the gas infrastructure can continue to play an active part in a decarbonised world. This will deal with issues of how capacity in the gas network could be exploited to address the challenges faced by the power network (increasing wind, heat pump demand, storage and balancing). The impact (costs/carbon emissions) of shale gas on the development of the energy system (possibility of CCS technologies) will be addressed (this research will build on and utilise a review completed by UKERC on unconventional gas resources in the

UK (McGlade *et al.* 2012)). Other uses of the gas grid will be explored, such as the impact of bio-methane/hydrogen injection on the gas transmission/distribution system (costs, carbon reduction and technical/safety limitations).

Operational and planning network models will be used for this potential project. These models will have a spatial and temporal dimension to them. Scenarios will be used to investigate the role gas could play in a system with large amounts of renewables. Injection of bio-methane and hydrogen into the gas grid will be investigated. The impact on network operation and effect on appliances will be examined. A planning model will be used to assess the cost optimal approaches to exploring the role of the gas grid in the next few decades using various scenarios on exploitation of shale gas, CCS commercialisation, failure to decarbonise heat (through heat pumps) and storage capabilities of the gas grid.

The key output of this research will be to layout the possible roles that gas and the vast gas infrastructure could play over the coming decades as we decarbonise the energy system. Key technologies such as hydrogen/bio-methane injection and CCS that could prolong the use of the gas infrastructure will be investigated in terms of costs, carbon emissions and security implications.

3.3 Integration of new generation: control of offshore wind farms and Integration of EU electricity markets

Project 1: Control of offshore wind farms

A methodology to determine the Virtual Power Plant (VPP) capabilities of offshore wind farms and cluster electrical systems has been investigated and developed in order to enable offshore wind farms to contribute to control of frequency and voltage ensuring compliance with grid codes. In this context, fundamental research on active power and frequency control of wind generation has been carried out. The models developed enable the impact of different synthetic inertia control strategies to be assessed, which will have a direct effect on the required amount of frequency response services. To validate that VPPs comply with grid codes that impose reactive power and voltage performance which are defined as delimited areas on graphs formed by pairs of values such as active vs. reactive power curves, it is necessary to ensure that, as a minimum, the offshore system is capable of operating inside these areas. The developed model can assess operational constraints and capabilities to enhance operational flexibility whilst satisfying the grid code requirements.

The key objectives of control of offshore wind farms research were to investigate the concept of CPP for supporting frequency regulation and understand the alternative control strategies for synthetic inertia, both distributed or centralised; and investigate VPP reactive power capabilities and cost effective approaches to meeting offshore grid codes.

Reactive Power Virtual Power Plant Capabilities

In order to assess the VPP reactive power capabilities, a set of curves is built by computing power flows of a cluster test system with two similar wind farms. Each wind farm comprises 48 wind turbines with a rated output of 6.0 and 6.15 MW respectively, giving the total installed cluster capacity of 583 MW. Voltage level of the collection system array is 33 kV, and the collection point comprises two three-winding transformers (mounted on one platform). Voltage level of the export cables is 155 kV and these are connected to a hub; from there the system is connected to the onshore grid through an HVDC VSC system. The results of the tool were validated by comparing them with the results of the power flow engine of the Eurostag (2010) and PowerFactory (2013) software.

Application of P-Q-PF and L-PF-PF curves

P-Q curves are very useful for assessing reactive power cluster capability; however, this information can be enhanced by including the full operation range trajectory for each power factor set point of wind turbines. The graph in figure 23 shows a series of active vs. reactive power and power factor set point curves (P-Q-PF). The additional graph in figure 24 shows a series of active power losses vs. power factor and power factor set point curves (L-PF-PF), and delivers additional information to the designer for grid code and operator requirements by including power factor values at Point of Common Coupling (PCC) for the full operation range of wind turbines with their association to active power losses trajectories.

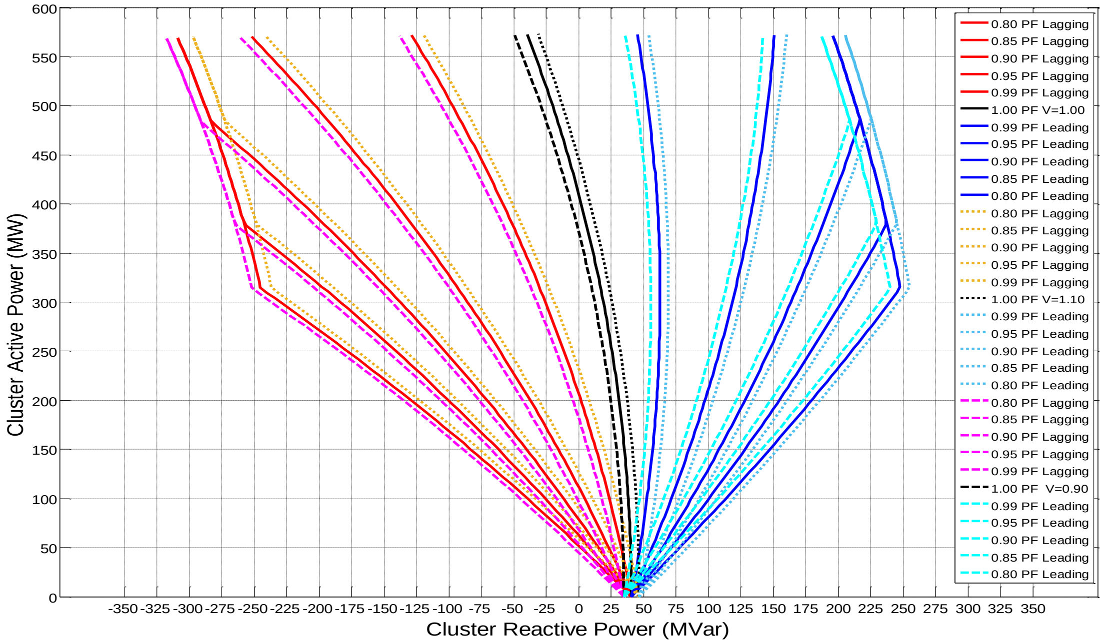

Figure 23: P-Q-PF curves with voltages at PCC of 0.9, 1.0, and 1.1 per unit

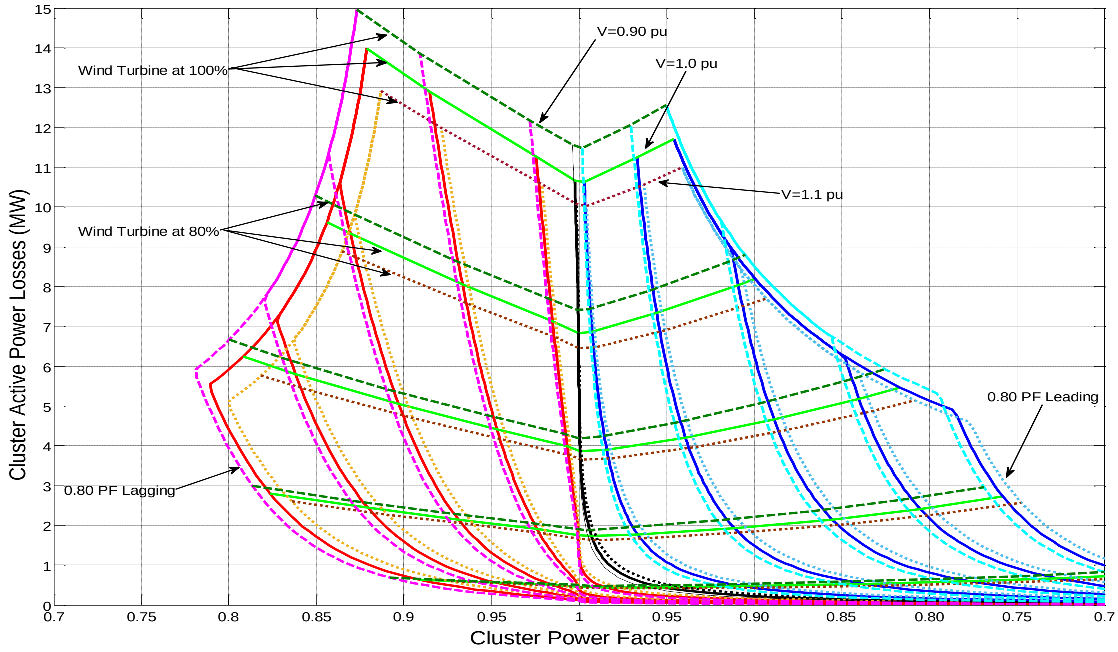

Figure 24: L-PF-PF curves with voltages at PCC of 0.9, 1.0 and 1.1 per unit

The purpose of P-Q-PF and L-PF-PF graphs is to visualise the reactive power capability of the cluster when voltage variations and/or allocation of equipment are incorporated in the analysis. Figure 23 shows P-Q-PF curves for three different voltages at PCC, 0.9, 1.0 and 1.1 per unit. When power factor curves are calculated with voltage of 0.9 per unit, these are on the left of curves calculated with voltage equal to 1.0. On the other hand, when voltage is 1.1per unit the curves are on the right. This displacement happens as well in L-PF-PF graphs as is shown in Figure 24. The effect of voltage variations in the reactive power capability of the system is apparently minor; however the effect in the active power losses of the cluster system is perceptible. Figure 24 shows that voltages at PCC below 1.0 per unit increase consumption and decrease production of reactive power, as well increasing active power losses. In contrast, voltages above 1.0 per unit decrease the consumption and increase the production of reactive power with diminution of active power losses. The usefulness of the curves is validated when sensitivity analysis is carried out with diverse scenarios; such as size and allocation of compensators.

Active Power and Frequency Control

Wind turbines with variable speed technology such as Full Converter (FC) and Doubly Fed Induction generator (DFIG) have the flexibility to control the active power of individual turbines, and consequently of the wind farm (National Grid, 2010). The analysis presented in this subsection is focused in the latest state-of-the-art technology.

Case 1: Synthetic inertia response of wind system

This case evaluates the impact of wind penetration with synthetic inertia response in a representative GB system as shown in Figure 25. The system has an assumed demand of 25 GW, and a lumped wind generation system of 10 GW that is operated at 0, 2.5, 5, 7.5 and 10 GW, which correspond to wind speeds of 0, 7.01, 8.85, 10.23and 11.5 m/s, respectively. This system suffers a sudden 1.32 GW generation loss at the 100th second, and then the effect of synthetic inertia frequency response is evaluated for each wind output level. The loss of 1.32 GW has been selected because this is the maximum expected generation loss in the GB system, while 0.8Hz is the associated maximum permitted frequency drop in the system. It is highlighted that only active power increments (ΔP) are shown in all figures to facilitate comparison.

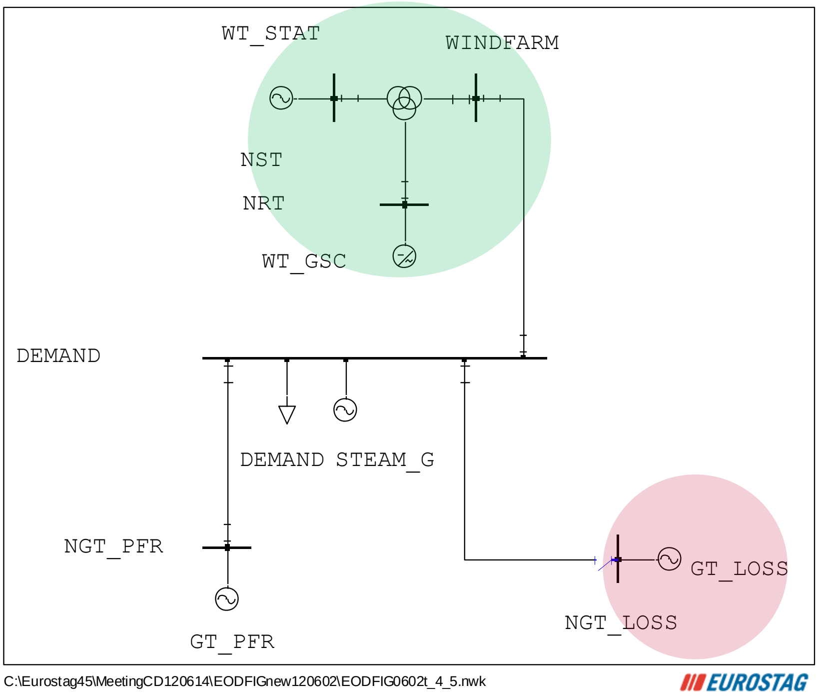

Figure 25: Test system for cases 1 and 2

Figure 26 shows the impact of synthetic inertia in the system, provided by wind generators. In order to assess the behaviour of system frequency, the same rotor speed reference change has been assumed for each output level of the wind generation system (i.e. wind speed). The graph on the left shows that the frequency response provided by the synthetic inertia is inversely proportional to the operation level, with more response being provided at lower output levels. This is also reflected in the graph on the right, where the minimum frequency drop takes place when wind generation is delivering 2.5 GW to the system (the response provided is better than when using only conventional generation). On the other hand, the maximum frequency deviation takes place when wind generators deliver 10 GW to the system. We also note that from the five operation levels, only two stopped the frequency drop above the limit of 49.2 Hz: the scenario that uses conventional generation only, and the wind output at 25%.

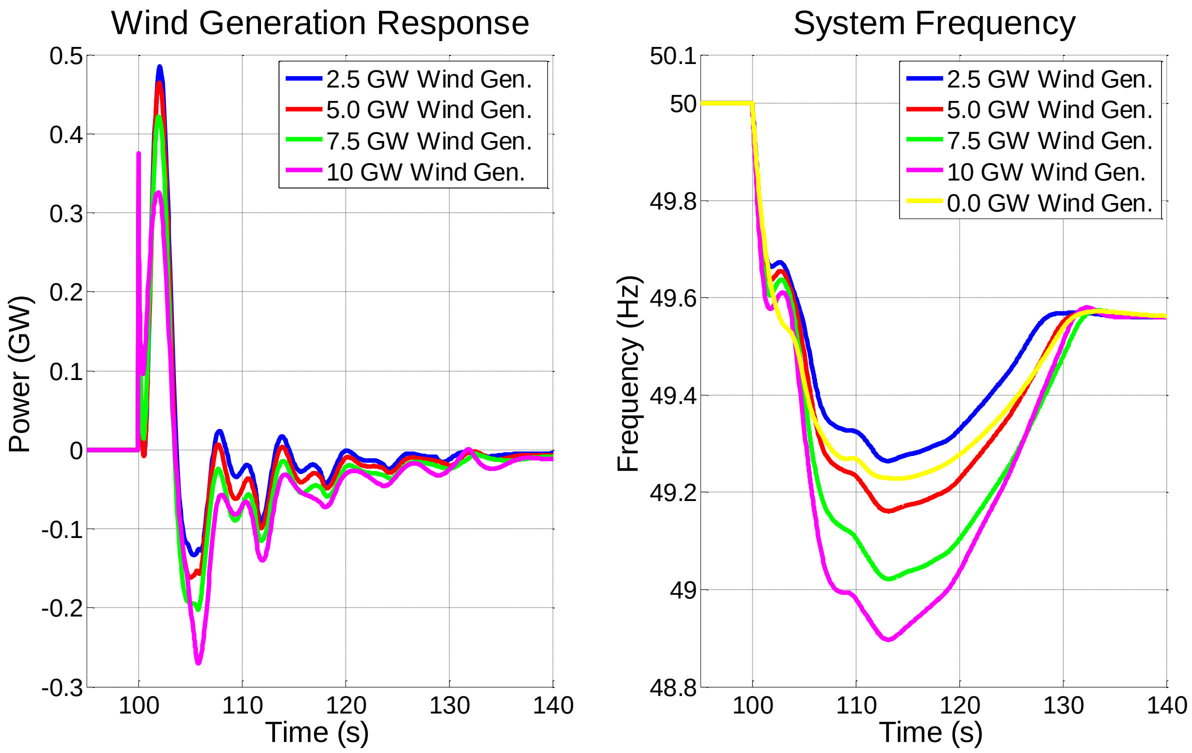

Figure 26: Case 1 Wind Farm Response and System Frequency

Case 2: Modified synthetic inertia response controller

With the aim of improving the worst response of case 1, which takes place when wind generation delivers 10 GW to the system, a heuristic synthetic inertia control strategy was implemented to the wind generation system and tested under the same event of generation loss of 1.32 GW. The graph on the left in Figure 27 shows the responses of original and modified synthetic inertia controllers. The green line shows that the heuristic strategy delivers energy in at least two steps, while the negative power increment is smoothed. The graph on the right shows that the frequency deviation is diminished and is stopped above the first controller used in case 1. Although the frequency drop is not stopping above the frequency deviation limit of 49.2 Hz, the improved performance achieved with the modified controller justifies further research into optimising the delivery of synthetic inertia.

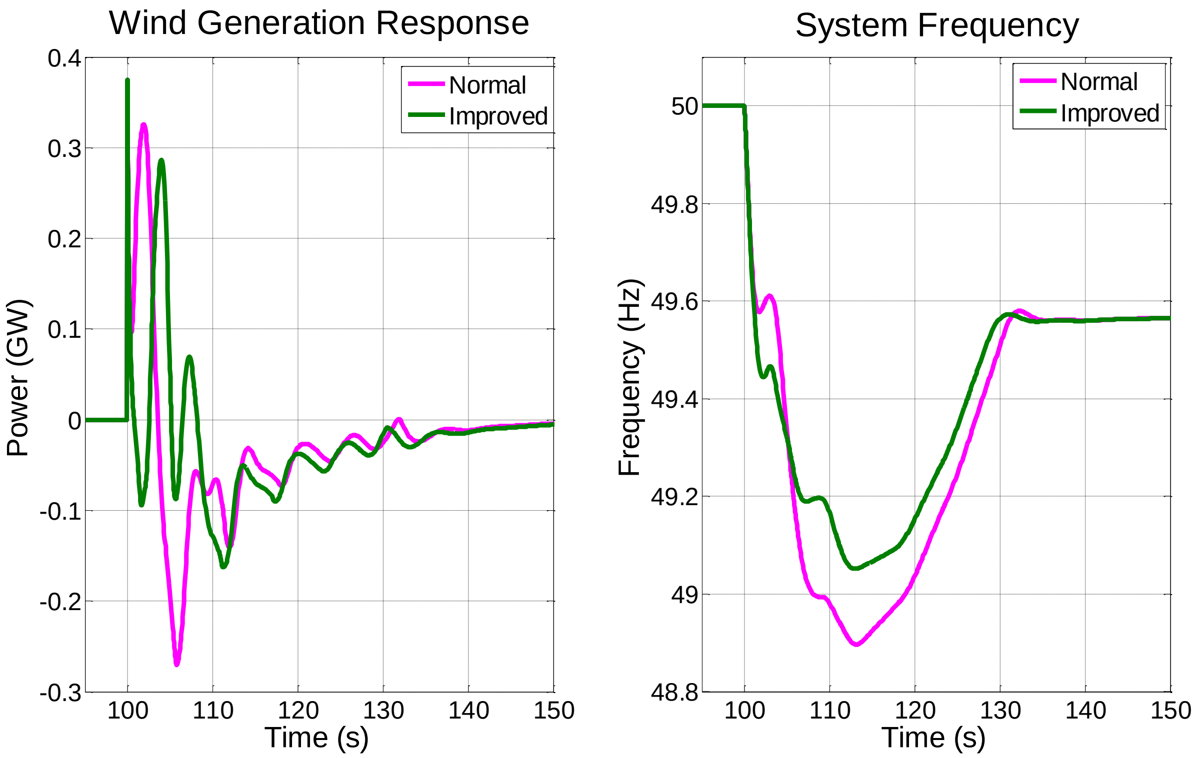

Figure 27: Case 2 synthetic inertia with and without heuristic controller

Project 2: Integration of EU Electricity Markets

EU electricity model was enhanced to quantify the benefits of different levels of integration of EU electricity markets considering further energy integration, integration of balancing markets and coordinated deployment of renewable energy source across EU. The key outputs of the enhanced DSIM include asset investment (generation, storage and network), system operation costs (generation dispatch, scheduling of storage and demand response, allocation of operating reserves, system operating costs, renewable curtailment, power flows), security of supply index, CO_2 emissions, and wholesale electricity prices. The benefits of EU wide, versus Member State centric approach to energy development are investigated and quantified.

The key objective of integration of EU electricity markets research was to enhance the Dynamic System Investment Model, in order to examine the significance and quantify benefits of integrating EU electricity market that facilities efficient cross-border energy exchanges but also sharing the provision of short term system management services, such as frequency regulation and reserve, long term security of supply and EU wide renewable energy policy.

Whole-electricity System Investment Model (WeSIM)

WeSIM is a comprehensive electricity system analysis model that simultaneously balances long-term investment decisions against short-term operation decisions, across generation, transmission and distribution systems, in an integrated fashion as is shown in Figure 28.

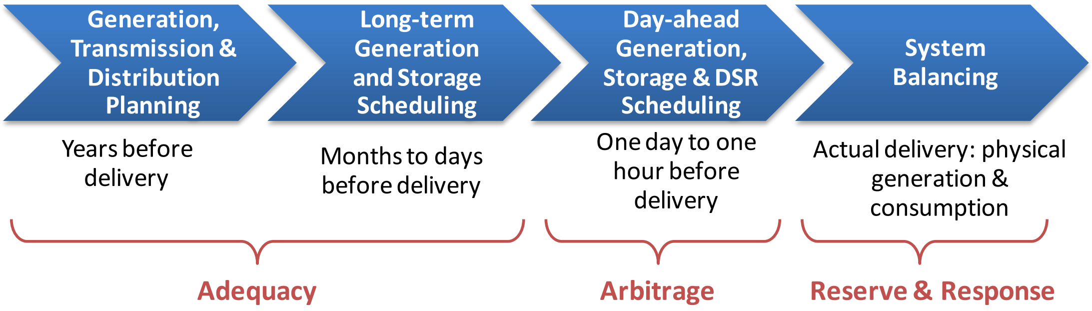

Figure 28: Balancing electricity supply and demand across different time horizons

When considering development of future low carbon electricity systems, including application of alternative smart flexible technologies such as demand side response (DSR), distributed energy storage, flexible network technologies and emerging designs of flexible generation technologies, it is important to consider two key aspects:

- Different time horizons: from long-term investment-related time horizon to real-time demand-supply balancing on a second-by-second scale (Figure 25); this is important as, for example, alternative smart technologies can impact system investment and operation cost (and carbon) performance simultaneously.
- Different assets in the electricity system: generation assets (from large-scale to distributed small-scale), transmission network (national and interconnections), and local distribution network operating at various voltage levels. This is important as alternative technologies may be located at different sites in the system and at different scales.

WeSIM carries out an integrated optimisation of electricity system investment and operation and considers (i) short-term operation with a typical resolution of half an hour or one hour (while also taking into account various frequency regulation requirements), which is coupled with (ii) long-term investment, i.e. planning decisions with the time horizon of typically one year (the time horizons can be adjusted).

The objective function of WeSIM is to minimise the overall system cost, which consists of cost of investment in generation, network and enabling technologies and cost of operating the system:

- The investment cost includes capital cost of various generating technologies, the cost associated with their flexibility characteristics, investment cost of energy storage technologies, capital cost of new interconnection capacity, the reinforcement cost of transmission and distribution networks including cost of emerging flexible network technologies.
- System operating cost consists of the annual generation operating cost and the cost of interruption driven by capacity inadequacies. The model captures part load efficiency losses and generation start-up costs, while taking into account dynamic characteristics of generating plant, which is a key aspect to quantifying system integration cost of renewable generation and role and value of alternative emerging enabling technologies, such as storage.

There are a number of constraints that need to be respected by the model while minimising the overall cost.

EU System and Application of WeSIM to inform policy

WeSIM is used to assess the electricity infrastructure development and system operation within UK or EU. Different network topologies will be generally used to balance the complexity and accuracy of modelling, an example of these EU topologies is shown in Figure 29. Different levels of market integration can be modelled in WeSIM through distinctive levels of energy exchanges cross-border, sharing of security or various operating reserves, e.g. country, regional, EU levels. WeSIM optimises the generation, storage, and demand side response dispatches by taking into account diversity of load profiles, renewable energy profiles (hydro, wind, PV, CSP) across Europe, in order to minimise the additional system capacity to meet security requirements. Finally, WeSIM simultaneously optimises investment profile in generation infrastructure and transmission networks capacity, while meeting security and CO_2 constraints as appropriate.

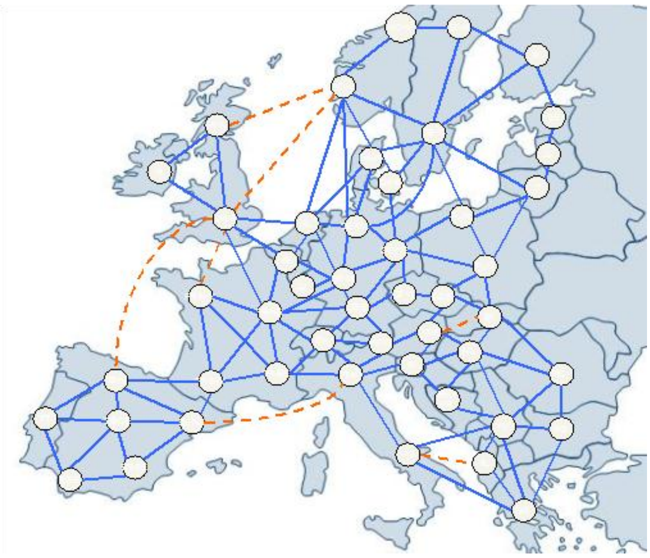

Figure 29: System topology used for studying the value of flexible balancing technologies

In the context of EU market intergration, WeSIM was applied to quantify inefficiencies in operation and investment associated with reduced levels of integration, particularly considering the impact of:

- Constraining energy and power exchange between regions / member states, due to lack of market compatibility or insufficient cross-border transmission investment. This will be particularly critical if energy exports from areas with significant renewable energy sources are limited. Given that wind generation will dominate renewable, generation production in the north of EU, while solar generation will be dominant in the south, constraining energy and power exchange between regions may limit the ability of the EU system to absorb renewable generation and hence lead to significant increase in costs of market operation and reduce efficiency in investment in renewable generation, potentially leading to very significant welfare losses that will be quantified. Integration of the EU energy Market can bring savings from 9 to 34 €bn/annum.
- Maintaining energy self-sufficiency and/or security of supply at a member state level, rather than allowing supply security resources to be shared among member states. Interconnection can bring significant benefits to security as this can significantly reduce the generation capacity margins in individual member states, while maintaining security of supply performance at historical levels. Self-sufficiently in terms of security of supply, mostly

practiced across EU at present will lead to significant increases in amount of backup power plant and the corresponding costs. Integration of the EU capacity Market can bring savings from 3 to 7.5 €bn/annum.

- Limiting sharing of various balancing services between countries and regions. Member state centric allocation of various reserves that prevents sharing of system management resources across regions will significantly increase the total cost of balancing demand and supply, which may be particularly relevant in low carbon systems with significant penetration of technologies with reduced flexibility (e.g. nuclear and less flexible CCS generation). Integration of the EU balancing Market can bring savings from 0.5 to 2 €bn/annum.
- Lack of EU wide market harmonization of with respect to support (subsidies) of low-carbon generation subsidies and/or carbon pricing. In particular, it will be important to assess the economic impact of country-specific renewable energy targets against EU-wide targets, which would lead to optimization of renewable plant citing, taking into account very significant variability in renewable resource availability across EU. Integration of the EU renewable policy can bring savings from 15.5 to 30 €bn/annum.

3.3.1 Conclusions and further work

Control of offshore wind farms

The output of the VPP reactive power capabilities tool is a set of curves that comprise results of an extensive number of simulations for multiple operation levels of the cluster electrical system. It was shown that these novel visual aids facilitate the analysis by assuring that a selected alternative can meet the required grid standard. As an additional feature, these visual aids can show the impact in the active power losses at different operational levels of the cluster which are associated with the adjusted power factor set point of the wind turbines. This difference in the amount of losses provides an incentive for further research to find the optimal set point for each reactive power and voltage controller of the offshore cluster system.

The need for and the value of frequency regulation services, required to deal with a sudden loss of large conventional power plant, will significantly increase in the future low-carbon GB system (Strbac *et al.*, 2012; Aunedi *et al.*, 2013), particularly because wind generation does not provide inertia and frequency regulation services. It is expected that the requirements for frequency regulation services may increase from today's level of around 1 GW to more than 5 GW by 2030. The models developed demonstrate that variable speed wind turbines could provide synthetic inertia and contribute significantly to stabilising future GB electricity system. Our work assessed that capitalised 2030 system value per kW of frequency response varied between around £2,600/kW and £4,600/kW for the inertia-based response requirement (and this is less that £400/kW at present), and this could provide additional income to offshore wind farms. We also observed that the system CO_2 emissions would reduce by 15% when wind farms contribute to the delivery of frequency regulation and hence displace coal and gas generators in providing frequency response.

Further work is required for overcome additional challenges, such as the decoupling introduced by the use of HVDC transmission systems and implementation of rapid frequency response in conventional power plants.

Integration of EU Electricity Markets

Given that the levels of long term reserve (backup capacity) and short term operating reserve requirements together with the need for flexibility will increase significantly in future, it will become increasingly important to optimize the provision of these services cross-border and benefit from diversity of renewable generation outputs and demand, as the system management at the member state level will have very significant cost implications and lead to increased CO_2 emissions (overall short term variability of renewable generation outputs is reduced when an EU wide perspective is adopted, due to significant diversity effect). As an example of the modelling conducted, we demonstrated that an EU wide approach, in contrast to a member state centric approach to security of supply, or in other words, an EU wide capacity market, would save about 100 GW of generation plant across EU in 2030, which can only be attributed to interconnection. The total benefits of fully integrated approach to decarbonising EU system were estimated to be in the range between €30bn and €70bn per annum.

3.4 Electricity Market Design for a Sustainable Low-Carbon Electricity Sector

It is essential to design the electricity wholesale market in way that is most likely to facilitate the development of a low-carbon electricity sector whilst maintaining energy security and ensuring competitive prices.

The UKERC Enery Supply theme research on this topic included two working papers on electricity market design for a low-carbon future and analysis of the extent to which economic regulation enables the transition to a sustainable electricity system (Baker *et al.*, 2009). As noted earlier in this report, this research has been complemented by other projects that have engaged with the policy debates and developments in electricity market design. These include research carried out by the TPA team (project on Electricity Cost Estimation Methodologies (Gross *et al.*, 2013)), the Energy Systems theme (research fund project on Carbon Capture and Storage: Realising the Potential (Watson *et al.*, 2012)), and the Energy Demand theme (the potential for energy efficiency feed-in tariffs as part of the Electricity Market Reform package (Eyre, 2013)). In addition, UKERC's two flagship projects for phase 2 included detailed analysis of investment in electricity generation (Blyth *et al.*, 2014) and of the design and regulation of more sustainable electricity markets (Mitchell *et al.*, 2014).

A number of regulatory and electricity market issues related to the transition to a low carbon electricity sector that had attracted little previous academic interest were addressed in the Energy Supply theme research. The work led to a number of papers and articles such as (Baker *et al.*, 2011). The research also led to two submissions to Parliamentary Select Committees and has been cited by several publications by other authors as well as PhD and MSc theses. Looking back, the papers successfully anticipated a number of regulatory and market reforms that have been introduced in recent years.

The main findings from two reports produced from this research are detailed below.

The Extent to which Economic Regulation enables the Transition to a sustainable Electricity System

This report reviewed the regulatory environment, market arrangements and industry practices that existed at the time of writing (2009) (Baker *et al.*, 2009) and considered the extent to which these were likely to hamper or enable the transition to a sustainable electricity system. The focus was the delivery of the UK's 2020 renewable targets and a number of issues were identified that could be problematic in terms of that delivery, including:

- regulation effectively penalised intermittent renewable generation both in terms of access to the grid and transmission charging,
- the electricity market arrangements (BETTA) were (and still are) inefficient in dealing with transmission congestion, which will increase rapidly with the deployment of wind and other renewable technologies
- Regulation and market arrangements encouraged traditional transmission investment over innovative and more cost-effective alternatives.

Since publication a number of developments proposed by the paper have become reality. For example, transmission access arrangements have been modified so as to remove some of the barriers faced by renewable generation, while Ofgem have recently indicated that they are minded to adopt a transmission charging regime that directly takes into account the fact that renewable and conventional generation effectively "share" transmission capacity, a major theme of the paper. The outcome will be that renewable generation, particularly generation situated in the North, will see a significant reduction in transmission charges.

Developing this "sharing" theme allowed UKERC to make a significant contribution to the revision of National Grid's Security and Quality of Supply Standards (SQSS), which now fully embrace the concept that intermittent and conventional generation share transmission capacity.

The project was also able to make a significant and unique contribution to Ofgem's Project TransmiT, the outcome of which will be the reduction in transmission charges applied to renewable generation referred to above. In terms of regulation, Ofgem's new network price control, RIIO, has introduced arrangements that should encourage a more objective comparison of "traditional" and "innovative" investment, again a major theme of the paper.

Network Regulation and an Electricity Market for a Low-carbon Future

This report identified characteristics that regulation and the electricity market would need to possess in order to be compatible with a low carbon future. In particular, the report concluded that, without external support, intermittent low-marginal cost renewable generation could never be expected to be economic in an energy only market that depended on scarcity pricing, and that the injection of large amounts of low carbon energy would cause conventional plant necessary for back-up purposes to be dependent on capacity support (Baker *et al.*, 2010). The potential increase in network congestion with the growth of intermittent capacity developed was highlighted together with the increasing need for, and volatility of, operational reserves. It was concluded that the US-style standard market design, where energy, reserve and the costs of resolving congestion are optimised simultaneously, was more compatible with a low-carbon future than the disaggregated market designs seen in Europe where these are optimised separately. The report also stressed the need for market and balancing arrangements that did not penalise intermittent technologies such as wind and which encouraged demand side participation as a means of managing increased supply-side intermittency in the most cost-effective fashion.

Again, the report anticipated a number of developments in market design that have occurred since publication, for example the increasing interest in capacity mechanisms in the UK and other European Member States and the introduction of "market coupling" within Europe, where energy transfers and interconnector congestion is resolved simultaneously. Ofgem's Balancing Mechanism Significant Code Review seems likely to adopt measures proposed by the report, such as a single imbalance price, while the smarter markets initiative is also taking forward some of suggested developments to facilitate demand side participation.

3.4.1 Research gaps and opportunities

Impact on price, cost and risks in a post EMR era

Renewable generation supported by government policies such as feed-in tariffs and Contracts for Difference under EMR are likely to contribute a growing percentage of the UK's electricity supplies by 2020 and beyond, but given their output fluctuates with the weather and therefore is likely to lead to greater variations in the pattern of power prices and use of reserve and balancing services.

The gaps and opportunities in a post EMR (Electricity Market Reform) world are to evaluate:

a. The impact of the EMR package on potential investment and power prices. Do the EMR packages need to be tweaked to reflect the significantly increased costs and risks for most low-carbon generators with costs that are largely fixed.
b. How can policies minimise the subsidies required (over time), by creating market designs that encourage efficient operation and investment decisions and by minimising the risks faced by generators.

Relationships between innovation, governance, policy/market design and affordability

Tackling climate change, whilst ensuring energy security and affordability are key issues facing energy the system within the UK and internationally. The goal of moving towards a more sustainable, low carbon economy implies the need for a radical transition in the way that energy is both supplied and used. Such a change not only links to the technologies that are developed and deployed, but also the wider political, social, and economic institutions and infrastructures in which they are embedded or with which they are connected, including all of the actors within them. This is a dynamic and complex process and the interactions between all these factors and the choices made by the different actors within the energy system, such as policy makers, large firms, new entrants, investors, end users, etc. will all influence that way the change occurs – i.e. energy governance.

In particular, this research will analyse the implications of different innovation and governance relationships on the success or otherwise of energy demand reduction, policy market design and issues of affordability. It will do this by exploring the means by which interactions take place within the energy systems and their implications for innovation in respect to carbon targets, technology deployment, investment, new practices, customer involvement, energy efficiency, and the total cost of energy for customers. Specifically the research will consider the relationships between institutions, policy design (such as rules and incentives for gas and electricity infrastructure and markets), industry structure, incumbent and new entrant company strategies and decision-making processes and consumer practices. The outcomes will lead to a better understanding of how the transition to a sustainable, low carbon energy system, can occur.

Compatibility of energy market and climate objectives

The aim of this project will be to model market driven investment into new electricity generation and flexible technologies under different market deigns and climate and energy policies in the period to 2030 and 2050, in the context of UK and EU. Specifically, the focus will be on assessing the performance of alternative market designs and providing evidence needed to understand the significance of the key factors like high capital intensity and low marginal costs, marginal cost based wholesale pricing, role of balancing and ancillary services market designs, the expected evolution of carbon prices, role and market value of various types, levels and responsiveness of electricity demand and profitability of investment in energy storage and other flexible technologies. A novel whole-system energy market model will enable investigation, for the first time, the interdependencies between decarbonisation objectives and ability of the markets, combined with the EU Emissions Trading System (ETS) carbon market, to generate the necessary investment incentives for a decarbonising power sector. Furthermore, this will include evaluation of alternative ancillary services and capacity mechanism options, decentralised market or centralised / location specific auction based incentives to enhance system flexibility and facilitate cost effective integration of intermittent renewable generation in the system.

4. Summary

The UK power system experienced a period of significant and rapid expansion during the late 1980s and in the 1990s. Many power generation assets are now approaching the end of their useful life and need to be replaced as we decarbonise the overall energy system. Developments in distributed generation and other technologies open important questions as to whether the traditional approaches to development and operation of power systems are still adequate and whether the anticipated major re-investment in transmission and distribution networks could be avoided by adopting new technologies such as smart grids, smart meters and a greater emphasis on demand side participation. Additionally, the possibility of greater interconnection (for both gas and electricity systems) could provide a multitude of benefits (better use of geographic resources, cost reductions etc.) but also present concerns such as the extent and impact of market harmonisation (Europe wide single markets for gas and electricity), rules for addressing supply shocks (especially if they occur in other countries) and social and geo-political issues.

The UK gas supply system has undergone large changes over the past decade, going from self-sufficiency to relying on imports from Europe and beyond via LNG supplies. As we move towards a low carbon energy system the impact on the gas transportation system will need to be reassessed and questions on the viability of gas infrastructure opens a plethora of questions. Natural gas is the main energy source used for the generation of heat in buildings. However, growing concerns regarding climate change and energy security opens the possibility of either greater electrification of heat supply (through heat pumps) or other methods such as district heat systems supplying low carbon heat for homes. The impacts of these energy system transformations on costs, security, social and environmental issues are opportunities for further research.

High level research issues identified within the UKERC Energy Supply theme cover a number of areas, including:

- Aging infrastructure – replacement strategies before failure ➔ models and tools for condition monitoring ➔ risk management of existing T&D infrastructure

- Energy security & system security
- Environmental sustainability – reducing the impact of electricity production, transportation and use on the environment (strive to reduce greenhouse gases responsible for climate change) ➔ need to incorporate climate change driven constraints into system planning and operation (EU renewables targets; 80% 2050 CO_2 targets; Meeting UK carbon budgets will require large scale decarbonisation of the electricity sector by 2030)
- Integration of distributed generation including intermittent energy technologies & micro generation ➔ what type of network architecture ➔ reliability and power quality➔ communication and control aspects of networks ➔ incorporation of demand response and demand side participation (impact of smart meters)➔ role of energy storage
- Incorporation of smart meters and smart grids (impact on demand and networks)
- Transmission (on- and offshore) and distribution network planning under uncertainty of intermittent renewable resources such as wind and the uncertainty of markets and regulatory policy
- Interaction between electricity and gas networks ➔ Integrated network (multi energy vector) research and optimisation
- Encouraging network innovation and low carbon generation through regulation and market design
- Assessing the potential of heat networks
- Impact of greater European market/network integration (gas and electricity)

From these high level research issues, some of the key research challenges identified in synthesising the Energy Supply theme projects are summarised as follows:

Identifying and quantifying the costs and benefits of community heating and energy systems

Electricity and gas networks are traditionally assumed as the most important energy infrastructure systems. Around 52% of gas is used to provide heat for buildings and industry and 34% is used in power stations to produce electricity in the UK. Natural gas is the main energy source used for the generation of heat in buildings. However, growing concerns regarding climate change and energy security forces to seek other methods of supplying low carbon heat for homes.

Community energy systems are important as they enable features specific to a community to be identified and thereby exploited. This is of particular importance to heat, for example, where the “fuel agnostic” nature of district heat systems allows the utilisation of different energy sources, which traditionally are not considered. For example, sewage water systems could be a potential source of energy for heat pumps. Also the local geography may offer potential heat and cooling sources, e.g. aquifers, as well as opportunities for storage. Another example is where the local production of biogas or unconventional gas which can be used to supply communities directly for both their heat and transport or indirectly via CHP plant.

At regional and district level a complex interaction between energy, water and solid waste management infrastructure systems may occur in the future. Therefore, a holistic approach must be adopted to understand these interactions and to investigate how the integration of different utility infrastructure systems could help to reduce carbon emissions, and increase energy security and affordability.

The key output from this potential research area will be a community multi vector energy and utility infrastructure investment model that incorporates local geography to enable investment propositions to be evaluated. In addition the model will enable operational performance of community energy systems and smart integration benefits from building level and beyond to be determined. The research will identify the performance of community energy systems relative to national and/or regional scale energy systems. In particular the following research questions will be addressed:

- Can community energy systems offer benefits over traditional large energy systems in terms of energy security, affordability and carbon emissions?
- What needs to happen to gain improvements?
- What is the scale of the opportunity for community energy systems?
- What are the barriers (social, technical, economic) to their development and what support is required?
- What are the potential benefits from integrating community energy systems with other utility infrastructure such as water and solid waste management?

The research will assist policy makers as well as community energy systems and regional planners. At a community level the research will support the evaluation of specific investment decisions as well as providing evidence for gas and electricity network investment under the RIIO framework.

Quantifying Costs and Benefits of Integrating UK and EU Energy Infrastructures

UK and European energy systems are facing challenges of unprecedented proportions. In order to facilitate a cost effective transition to low carbon future an integrated energy infrastructure development will be critical. Regarding the electricity sector, there are major unanswered questions regarding the full value that interconnection could provide in delivery and management of renewable generation. Furthermore, the importance of coordinating development of North Seas Grid infrastructure is not fully understood. Moreover, the criticality of integration and coordinated development of gas infrastructure, for delivering efficient energy system operation and investment and security of supply, is yet to be investigated. Also, hydrogen as an energy vector could play an important role in mitigating challenges of integration of renewables through decoupling of supply and demand around heat and transport sectors, although, however, the value of hydrogen to the energy system, particularly in the context of EU energy systems, and implications for the infrastructure developments, is yet to be understood.

Smart meters and demand side participation

There is movement towards more closely monitored and controlled power systems, smart grids. The rationale is to improve asset utilisation, provide decision support for engineers, maintain security of supply, reduce losses and decarbonise the system through increasing connection of renewable and decentralised generation. There is concern, however, that control based on new automated data and information flows may lead to a more complex and therefore less predictable system. To counter this, the domain areas of existing software and hardware models must grow – allowing researchers to rigorously prove new control ideas. For instance, models spanning multiple timeframes, voltage levels and energy vectors may be required.

The proposed GB smart metering system represents a significant increase in access to the demand side from the system operator perspective. Smart meter functionality will include demand response via direct interaction with appliances, half hourly time of use tariffs or the remotely operable supply disconnect switch . The effectiveness of increased demand side involvement in power system control, through active or automated participation, is uncertain – both from domestic and non-domestic demand. Also, there are questions around which parties (e.g. DNOs, suppliers, system operator) should have control of demand response and how it should be regulated. The extent to which smart metering could or should be used to verify demand response action also remains largely unknown.

There is a research area around how smart metering data and functionality can be used to improve network hosting capacity of localised generators, heat pumps, electric vehicles and energy storage. This leads to the area of automated control on a localised scale and raises the question of how local control schemes should interact with the system at large. Experimentation with and testing of new control equipment and philosophies is therefore an important research area. Hosting capacity may also be increased through using retrospective examination of data to inform network improvements (e.g. network configuration). How smart metering data should be turned into information and presented to network operators and planners is therefore a valuable research question that precedes the development of visualisation and decision support tools.

Gas networks research

a) The role of gas in the UK energy system:

Natural gas has played a key role in the UK energy mix over past few decades. We move into an era where carbon emissions, security and affordability are key drivers that will shape the future energy mix. The question is what role will gas play. Will it simply play a transitional role and be phased out as renewable and low carbon technologies increasingly become more attractive or will shale gas (‘fracking’) help maintain the status quo.

The key output of this research will be to lay out the possible roles that gas and the vast gas infrastructure could play over the coming decades as we decarbonise the energy system in a cost effective manner whilst ensuring security of energy supplies. Key technologies and capabilities such as hydrogen/biogas injection, greater European interconnection with UK providing an import hub role and CCS that could prolong the use of the gas infrastructure will be investigated in terms of costs, carbon emissions and security implications.

b) Resilience of gas systems:

There are numerous energy system scenarios depicting how the UK can meet its carbon and renewable targets but far less consideration has been given to the resilience and security performance of these scenarios. Therefore the key output of this research will be a comprehensive set of indices that will describe the vulnerability of the system against different outcomes across a full spectrum of future system scenarios. Multi-energy vector computation of key performance indices will allow quantification and establishment of metrics that could be used to facilitate decision-making for policy makers and system operators regarding set of optimum actions to take on investment (gas vs. electricity) to hedge the risk against escalation in technology cost and resource or infrastructure availability shocks.

Compatibility of energy market and climate objectives and risks in a post EMR world

There is a broad agreement of the various 2050 roadmaps that, for reaching the long-term climate objective of 80% greenhouse gas emission reductions in 2050, the decarbonisation of power generation is necessary. High capital intensity of many low carbon power technologies, an increased number of new market actors due to the growth of decentralised renewables and an increasing share of intermittent renewables have raised new questions regarding the appropriateness of electricity market structure and design to enable the necessary investments for decarbonising power sector while ensuring security of electricity supply and efficiency of its operation. As a result, there has been a recent surge of market and carbon pricing reforms and interventions to ensure sufficient investments in both low carbon technologies and peaking capacity through either obligations or auctions (for instance the EMR package). Furthermore, efficient real-time demand-supply balancing with a significant penetration of intermittent wind power and increased contribution from less flexible low carbon generation will become a major challenge.

The lack of flexibility and reduction in system inertia, 20% of renewable generation may be curtailed in 2030, which would undermine the case for renewable investment and deteriorate the emissions-related performance of the system, as the full emission saving potential of renewables may not be realised. There are opposing views regarding the extent to which an efficient market can facilitate investment in flexibility to ensure cost effective integration of variable renewable generation.

The development of a whole-system energy market model will enable investigation, for the first time, the interdependencies between decarbonisation objectives and ability of the markets, combined with the EU ETS carbon market, to generate the necessary investment incentives for a decarbonising power sector. Furthermore, this will include evaluation of alternative ancillary services and capacity mechanism options, decentralised market or centralised / location specific auction based incentives to enhance system flexibility and facilitate cost effective integration of intermittent renewable generation in the system.

The impact on price, costs and investment in a post EMR (Electricity Market Reform) world was identified as a research area, specifically:

a. What is the impact of the EMR package on potential investment and power prices? Do the EMR packages need to be tweaked to reflect the significantly increased costs and risks for most low-carbon generators with costs that are largely fixed?
b. How can policies minimise the subsidies required (over time), by creating market designs that encourage efficient operation and investment decisions and by minimising the risks faced by generators?

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