Managing Heat System Decarbonisation

Comparing the impacts and costs of transitions in heat infrastructure

Final Report – Annexes and literature review

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8. Annex A – Gas network repurposing cost analysis

Since 2002 the Iron Mains Replacement Programme (IMRP) has been decommissioning old cast iron mains gas pipework within 30 metres of properties and replacing it with new polyethylene pipes. As the duration of the programme is 30 years it is often referred to as the "30/30 programme". The programme's objective is to address concerns regarding the potential for old metal pipework to fail and the consequent risk of injuries, fatalities and damage to buildings[1].

Cast iron pipework cannot be used for hydrogen as it is susceptible to embrittlement and fracture due to the diffusion of hydrogen into the metal. A potential benefit of the IMRP is that the new polyethylene pipe is suitable for hydrogen transportation, and as a consequence the very substantial investment that would otherwise have been required to repurpose the gas network to carry hydrogen has already been incurred.

Nevertheless, there will be additional costs as well as other technical and engineering challenges that must be addressed - these are estimated in this paper and will be further quantified by the H21 Leeds Citygate project[2] being run Northern Gas Networks.

The IMRP is also helpful in assessing the impact of infrastructure transition as it is probably the largest street works programme undertaken in the UK, and bears many similarities to the LV circuit reinforcement for electricity, which would become necessary in the event of the large scale deployment of heat pumps.

In 2011 the HSE and Ofgem published a report[3] which reviewed the programme. This included the costs incurred to date and those projected to 2032. Up until 2009/10 nearly 20,000 km of gas mains had been replaced at a cost of nearly £5bn. However, nearly £3bn of this would have been incurred due to normal replacement anyway and so the incremental cost of the IMRP programme is just over £2bn (in 2009 money) which is equivalent to £2.5bn in 2015 money[4]. The report also presents a projection of future IMRP costs to 2032 for the remaining 90,000km of gas mains. These costs total over £18bn in 2015 money undiscounted. Hence the total undiscounted cost of the IMRP is £21bn which is equivalent to an average cost of circa £1,000/household.

For gas network repurposing, the IMRP costs can be regarded as a sunk cost. The additional repurposing costs arise in association with upstream or higher pressure gas network along with changes to ancillary equipment such as controls, meters and instrumentation. In the repurposing costs, an estimate equivalent to 20% of the total IMRP cost has been made to cover this.

Further costs will be incurred as networks are transitioned from natural gas to hydrogen. Each household/building would need to have its gas installation inspected to identify the gas appliances that will need converting and any other operational or safety issues needing attention. Typically, an area for changeover would comprise 2,500 households (the average on an easily isolatable part of the gas network), so assuming a gas technician could convert 3 households/day, it would take a team of 40 technicians a month (20 working days) to complete. In addition, there will be programme costs for each Gas Network Operator. The resultant total cost for each household is therefore estimated at about £300/household and this is shown in the Table 2 below.

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[1] http://www.hse.gov.uk/research/rrpdf/rr888.pdf

[2] See ref. 15

[3] See ref. 87

[4] Office for National Statistics. "Consumer Price Indices."

Assumptions		**Reference**
Households (million)	Total	26.0
	Households connect to gas	22.0
	Nos of households to be converted to hydrogen	10.0
Hydrogen repurposing costs	Duration of programme, y	10.0
	Nos of Gas Distribution Networks	5.0
	Nos of household conversions per team per month	2500.0
	Nos of man days to commission each household, days	0.3
	Nos of contractor staff in a team to complete in 1 month	41.3
	Nos of contractor team to complete programme	33.3
	GDN programme team	20.0
	Total staff	1475.0
	Average FTE salary + 20% contribution to overheads (£kpa)	60.0
	Contractor cost (£Mpa)	82.5
	Upstream repurposing costs (20% of IMRP- £/household)	200.0
	Traffic management & other street works costs of contractor cost (%)	0.1
	Traffic management & other street works costs (£M)	8.3
Total costs	Planning team cost (£Mpa)	6.0
	Total upstream cost (£Mpa)	200.0
	Total cost (planning and contractor staff, parts and overhead - £Mpa)	296.8
	Total cost (£/household pa)	29.7
	Total cost (£billion)	**3.0**
	Total cost, £/household	**296.8**

Table 2 Gas repurposing costs

9. Annex B - Electricity network reinforcement costs

One proposed option to replace residential natural gas heating systems to support the UK's 2050 greenhouse gas emissions reduction target, is the wide scale deployment of electric heat pumps. Modelling and analysis were developed for this project and illustrate the potential impact of such a retrofit scheme as part of a nationwide programme of low voltage (LV) network reinforcement, similar to the gas Iron Mains Replacement Programme (IMRP), for 10 million households. Many of the conclusions, other than the overall duration, would be similar for programmes of larger or smaller scale.

This analysis constructs a reference case with high and low sensitivities, all based on a 25-year programme of LV network reinforcement. The following sections list the cost and network data as well as the assumptions underpinning the analysis.

9.1 Housing types – suitability for heat pumps

For new build developments with heat pumps the electricity network will be designed to meet the heat pump load from the start. It is also practical to consider ground source heat pumps for new build.

For the retrofit programme, it is assumed that areas need to be zoned for each solution - e.g. heat pumps, repurposed gas grids (using hydrogen) or district heating - in order to avoid multiple, competing infrastructure solutions which would not be economic.

The areas prioritised for heat pumps will have building types, local geography and occupation patterns that are most compatible with heat pumps, so it is assumed that in these locations this will be the dominant solution. Consequently, heat pump clustering on a circuit will be high and the affected circuits will require reinforcement to address thermal capacity, circuit voltage drop[5] and loop impedance[6], which could be problematic, with heat pumps kicking in frequently and causing local voltage dips.

Out of a total of 26 million existing households[7], there are circa 22 million currently connected to the gas network, predominantly in urban and suburban areas and therefore (on the basis of the definitions used) electrically connected by underground cables, rather than overhead lines.

The breakdown of these gas connected households is:

- 5.7 million detached
- 6.0 million semi-detached
- 6.8 million terraced
- 3.4 million flats.

The remaining off-gas-grid households are mostly in rural areas with circa 2.5 million heated by electricity and the remainder by "other", e.g. solid fuel or oil. For the purposes of this exercise, which is primarily about the large scale impacts on the electricity system, rural areas are not considered, even though they may offer an isolated, energy efficient electrical heating option in some cases.

Flats are not considered for large scale heat pump installation due to:

- The heat demand being lower and direct electric heating potentially being more economic.
- Limitations on water storage and space (internal and external)
- Visual and noise impact.

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[5] Voltage drop is a function of circuit loading and should not exceed 6%.

[6] When inductive devices such as heat pumps are switched on they can draw a starting current which may be several times normal levels. This can give rise to a temporary voltage dip or flicker which is predominantly determined by the loop impedance of the circuit and which should not exceed specified standards.

[7] www.delta-ee.com/images/downloads/pdfs/Delta-ee_ENA_Full_Report.pdf.

Therefore, electrical network reinforcement is primarily required to support air source heat pump installation in detached, semi-detached and terraced properties, connected to underground LV circuits in urban and suburban areas. An illustrative mix of households for a programme of 10 million could be:

- Detached – 3 million
- Semi-detached – 3 million
- Terraced – 4 million

9.2 Peak capacity

LV network design makes an assumption about the maximum demand for individual households connected to the circuit. This is referred to as the After Diversity Maximum Demand (ADMD) and is used in the design of electricity distribution networks where demand is aggregated over a large number of customers. It incorporates an assumption on the peak coincidence factor (PCF)[8] which typically could be between 5% and 10%. For a 3-bedroom property with gas central heating the guidance provided by UKPN engineering design standard[9] is that the ADMD is 1.5kW which would mean that for an LV circuit connected to 100 such households the circuit rating should be 150kW.

The installation of heat pumps will not only significantly increase overall household electricity demand but also the peak coincidence factor. This is because the heat pump will be operated at specific peak times and for sustained periods, particularly under cold weather conditions, e.g. high space heating and hot water demand in the morning and early evening periods in the winter.

A 8.5kW_{th} heat pump, which is typically suitable for an average sized household, will add to household peak electricity demand by about 3kW[10]. (For larger properties this may be even more if they require a larger heat pump, e.g. the largest single phase heat pump commercially available is 14kW_{th} with an electrical rating of nearly 5kW.) Together with the greater common usage patterns, this could result in an increase to the PCF for heat pump load of up to 50%, and possibly even higher under very cold weather conditions. Consequently this would increase the ADMD for the household from 1.5kW to 3kW and so if all the households installed a heat pump it would result in a doubling of the maximum continuous rating of the circuit from 150kW to 300kW.

This could worsen under very cold conditions if the heat pump is unable to provide the heat demanded by the building and thus may result in the householder supplementing the heating using resistive heaters such as fan heaters. Alternatively, hybrid heat pumps could provide supplementary heat using gas and so this risk would be reduced. In this case, it may also be possible to install a lower rated heat pump, e.g. 5kWth instead of 8.5kWth. Although these have an electrical rating of just under 2kW and should reduce the circuit's ADMD, they will need to operate at higher load factors or usage patterns to compensate for lower output thereby increasing the PCF. Consequently, circuit reinforcement is still likely to be required.

9.3 UK electricity network data[11]

- 155,000km of 11kV underground cable and 170,000km 11kV overhead line.
- 330,000km of LV underground cable and 65,000km LV overhead line.
- On average 100 households are connected to a single ground-mounted LV transformer[12].
- There are 26 million connected households.

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[8] This is the peak circuit demand divided by the sum of the peak demand of the individual components. It tells how likely the individual components are to peak at the same time. The highest possible coincidence factor is 1, when all of the individual components are peaking at the same time. Also see ref. 41

[9] UKPN Engineering Design Standard 08-0136.

[10] heating.mitsubishielectric.co.uk/Products/Documents/PUHZ-(H)W50-140VHA(2)YHA2%20PI%20Sheet.pdf

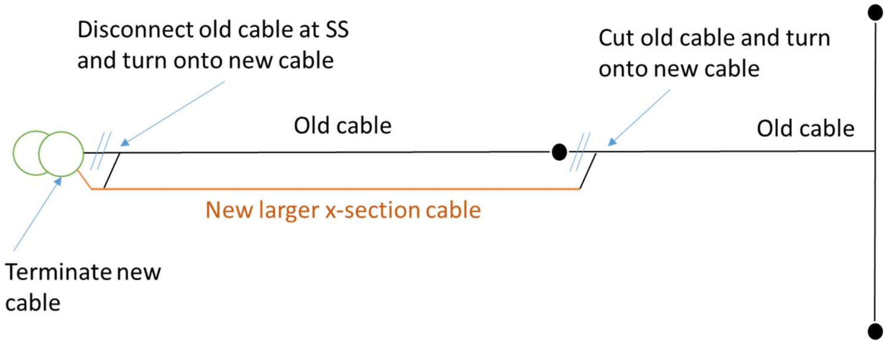
[11] Electricity Industry Review (Rev 18 based on data available at Apr 2014) published by Electrica Services

[12] In practice the variation in ground-mounted transformer sizes deployed is wide (200kVA – 1000kVA) and hence similarly the number customers supplied. However, the smaller transformers might typically support one or two separate LV cables, whilst the larger transformers would support four or more. (Evidence from Dave Openshaw for this paper)

This equates to an average LV network length feeding 100 households from an LV transformer of 1.5km. This includes the service connections (5m/ household on average), so is equivalent to an average circuit length excluding the service connections of 1km. Hence 10 million households would be served by around 100,000km of LV network.

9.4 LV network reinforcement methodology assumption

The methodology assumed for the purpose of this paper is shown in the figure below. In practice the applicability of this methodology will depend on the rating of the existing cable and the extent to which tapering has been used (i.e. cable cross-section reducing towards the remote end of the circuit):



The steps in this are:

- Disconnect old cable from substation and connect new cable
- Connect old cable to new cable at the substation
- Lay new cable from the substation to the intermediate connection point
- At approximately 30% of the circuit length from the substation cut the old cable and connect the new cable to the remaining 70% of the circuit length.

The important point to note is that the service connections from the old cable to the households are not disturbed, thereby substantially reducing the amount of work required. However, there will be branches and so the length of the new cable is likely to be longer than the 'ideal' 30% above. The model assumes 50% (with sensitivities of 30% and 60%) so, based on a starting length of 100,000km, an additional 50,000km of new cable would be installed (with sensitivities of 30,000km and 60,000km).

9.5 LV substation reinforcement

Many LV substation transformers are operating well below their maximum rating (perhaps around 40% on average[13]) and so could probably withstand a temporary overload, particularly as this is likely to occur under cold weather conditions and will be for relatively short periods. Hence, although it is assumed that all LV circuits feeding households with heat pumps will need reinforcing, it is likely that only 50% of LV transformers need to be upgraded (with sensitivities of 25% and 75%).

9.6 Traffic management and other street works cost

An assumption is made that there is sufficient space to trench and install the new cable in footpaths, although in some cases it could be necessary to excavate cable trenches in the carriageway.

Street congestion is a major factor in dense urban areas such as central business districts but may be less elsewhere. However, there will always be costs associated with permitting for traffic management, security, etc. An estimated on-cost of 10% has been added to installation staff costs to cover this (with sensitivities of 5% and 20%).

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[13] Based on winter cyclic loading rating

NB there will also be a social and economic cost associated with disruption and inconvenience to traffic and pedestrians which is not included here.

9.7 Asset replacement

If, as with the gas IMRP, there was already an established need to replace the existing LV cable assets, then the incremental cost of upgrading the system to support heat pumps would be considerably reduced, e.g. just the marginal cost of the additional cable. However, there is currently no compelling evidence of a need for a national condition-based LV cable asset replacement programme. This is despite many of the existing street circuits being installed over 50 years ago but understandable if the cables have experienced relatively little thermal stressing and so have many years of life left in them.

There may be other benefits from a heat pump driven reinforcement programme, such as reduction in losses or lower maintenance and repair costs but these are not considered in this analysis.

9.8 11kV circuits

There will also be implications for higher voltage networks if heat pumps are widely adopted. The requirement at 11kV would be largely driven by security of supply standards, e.g. sufficient switchable capacity to deal with loss of one circuit and to restore supplies within 3 hours in the event of an unplanned outage (for demand groups above 1MW).

Assumptions made about 11kV circuit reinforcement:

- Only the underground cables in urban and suburban areas will be affected
- 75% (with sensitivities of 60% and 90%) of circuit length is associated with household supplies
- Lower peak coincidence at 11kV means that about 50% of these would need reinforcement (with sensitivities of 25% and 75%)
- 10 million out of 26 million households are affected, e.g. 38% of total possible

This results in 14% of the 11kV circuits having to be reinforced (75% x 50% x 38%). The sensitivities for low and high scenarios are 10% and 29%, respectively.

9.9 Transmission system and >11kV distribution system

The impact on the electricity transmission system and the rest of the electricity distribution system from 10 million heat pumps is complex and a number of factors need to be considered, e.g. other changes in residential demand (such as embedded generation and electric vehicles), security of supply, etc.

Over 90% of the transmission system and over 70% of the >11kV distribution system is overhead line, and is likely to be more tolerant to higher load conditions, particularly as they are most likely to occur under cold weather conditions. Additionally, there is likely to be greater diversity of demand as the circuits will be supplying a much larger geographic area and will also serve businesses and industry so, for the purposes of this exercise, no additional costs for network impacts at greater than 11kV have been considered.

9.10 Annual work programme

The gas IMRP covers 110,000km of gas pipe replacement and installation has been limited to 3,580km.pa over 30 years in order to avoid excessive disruption to the public.

The total LV and 11kV circuit length to be reinforced in the reference case is 72,500km. A similar replacement/reinforcement rate over 25 years commencing in 2025 would mean the installation of about 3,000km pa (over 200km per DNO each year).

9.11 Staff and overheads

To undertake such a programme, each DNO would need to establish cable installation teams (including street-work staff or contractors), together with planning and support staff (engineers, designers, contract management, administrative staff, customer liaison, etc.), who would be specifically tasked with the programme of network reinforcement.

If each circuit (LV and 11kV) takes a month to be reinforced, this would mean that there would need to be an average of 29 installation teams each reinforcing 12 circuits each year. If each of these teams comprises 10 FTEs (Full Time Equivalents) working simultaneously and is supported by a central team of 50 FTEs this would result in a total programme team (including contractors) of about 340 FTEs per DNO.

9.12 Results

Table 3 below summarises the results of the analysis. For the reference case the total undiscounted cost is about £21 billion, with low and high sensitivities of £13 billion and £30 billion. This equates to about £2k per converted household in the reference case (between £1k and £3k including the sensitivities). This range appears credible (judged in orders of magnitude) when compared with the gas IMRP which has an undiscounted cost of £21billion and a cost per household of about £1,000.

Assumptions		**Reference**	**Low**	**High**
Households (million)	Total	26	26	26
	Heat pump conversions	10	10	10
LV circuits	Households per circuit	100	100	100
	Average circuit length (km)	1	1	1
	No. of circuits affected	100,000	100,000	100,000
	Average length to be reinforced	50%	30%	60%
	Circuit length to be reinforced (km)	50,000	30,000	60,000
LV substations	No. to be upgraded	50%	25%	75%
11kV UG circuits	Total length (km)	155,760	155,760	155,760
	of which residential	75%	60%	90%
	of which converting to heat pumps	38%	38%	38%
	of which will require reinforcing (estimate)	50%	25%	75%
	Resultant proportion of circuits to be reinforced	14%	6%	26%
	Circuit length to be reinforced (km)	22,196	8,878	39,952
Material costs	LV cable (£k/km)	100	100	100
	11kV cable (£k/km)	300	300	300
	Substation upgrade (£k)	25	25	25
Programme (per DNO)	LV circuit length to be reinforced (kmpa)	143	86	171
	No. of LV circuits to be reinforced per year	286	286	286
	11kV circuit length to be reinforced (kmpa)	63	25	114
	No of 11kV circuits to be reinforced per year	63	25	114
	Programme duration (years)	25	25	25
	Time for circuit reinforcement (months)	1	1	1
	No. of installation teams	29	26	33
	Staff per installation team	10	10	10
	No. of support teams	1	1	1
	Staff per support team	50	50	50
	Total staff	341	309	383
	Average staff cost (+ 20% overheads) (£kpa)	60	60	60
	Total staff costs (£mpa)	20	19	23
	Traffic management + street works (£mpa)	2	1	5
	Annual staff and overhead cost (£mpa)	23	19	28
	Total staff and overhead cost (£m)	563	487	690
Total undiscounted costs (all DNOs)	LV cable (£billion)	5	3	6
	LV substation (£billion)	1	1	2
	11kV cable (£billion)	7	3	12
	Staff and overheads (£billion)	8	7	10
	Total (£billion)	**21**	**13**	**30**
	Cost per household converted (£k)	**2**	**1**	**3**

Table 3 LV network reinforcement costs (reference case with low and high sensitivities)

10. Annex C - District heating network cost analysis

The main cost of district heating is the heat network itself which is consequently critical to the scheme's economics. The incremental capital and running costs of heat production are dependent on the heat source but generally represents a much smaller proportion of the overall delivered cost. District heating consists of:

- Heat infrastructure – this is the main heat network connecting heat sources to ancillary plant such as pumps and heat substations and connections to buildings
- Service connections – these are the branches connecting the heat infrastructure network to buildings
- Heat interface unit (HIU) and metering – this is the interface between the consumer's heating system and the service connections.

Due to lack of familiarity and experience in the UK, there is significant uncertainty associated with these costs and a number of studies have been undertaken to investigate them and their influencing factors. District heating costs used here are based on Pöyry[14] in 2009, so prices have been adjusted for inflation to 2015[15] prices. These are shown in the table below for different household types. Pöyry states that costs in the UK are substantially higher than in continental Europe and cites the lack of UK experience with the technology. Although it suggests that there is potential for a 50% reduction in the cost of a district heat network, the impact assessments use these estimates.

	Household type			
	Suburban	**Urban**	**Flat**	**Rural[16]**
Heat infrastructure, £k	2.6	3.3	1.2	2.6
Service connections, £k	3.9	3.1	1.8	5.8
HIU and metering, £k	2.8	2.8	2.8	2.8
TOTAL, £k	**9.3**	**9.2**	**5.8**	**11.2**

This table is based on the original from 2009 below:

Table 35 from Pöyry[61] 2009 prices	**Household type (Pöyry definition)**			
	Semi-detached (Less dense)	**Semi-detached (Dense)**	**High rise flat**	
Heat infrastructure, £k	2.135	2.719	1.000	
Service connections, £k	3.198	2.598	1.500	
HIU and metering, £k	2.300	2.300	2.300	
TOTAL, £k	**7.633**	**7.617**	**4.800**	

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[14] Davies, G. and Woods, P. (2009). "The potential costs of district heating networks." DECC. London. UK.

[15] Office for National Statistics. (2014). "Consumer Price Indices."

[16] This is based on suburban costs but to account for the lower heat density of rural areas the service connection cost has been increased by 50%.

11. Annex D – Summary of expert panel results

11.1 Interview process

The interviews were conducted individually and mostly by telephone. The background to the project was summarised with emphasis given to identifying the deployment challenges of each option, and not to identifying the most favoured one, i.e. the underlying assumption was that each option was appropriate for large scale deployment.

The following 'high level' questions were posed:

- What needs to be done to repurpose gas networks, reinforce electricity circuits or construct heat networks?
- What is the timescale for implementation?
- What do we need to do to prepare for such a UK wide project?
- How long would it take to mobilise sufficient capacity and capability?
- What scope is there to automate or speed up the works through investment in technology?
- What are the main obstacles to implementation that must be addressed, e.g. planning process, road closures, etc.?

The individuals selected for interview were chosen for their expertise and knowledge in the planning and construction of distribution networks and in particular those involving street works. In addition, two interviews were held with those with Danish expertise of heat networks.

11.2 Electricity

The interview was held with David Openshaw who is a Senior Advisor with UK Power Networks who has experience in all aspects of electricity distribution from a career involving front-line operations (construction, maintenance, fault location, testing and commissioning) as well as design and planning, strategic asset management and 'smart grids'. The outcomes were corroborated by other representatives from the sector representing over half of all DNOs.

It was concluded that the main impact would be the required level and cost of network reinforcement. Most electricity reinforcement until now has been done at 11kV and above, with very little at residential household voltage levels. Distribution circuits for residential households are typically designed assuming very low coincident use due to the level of intermittency of most electric loads, e.g. kettles, showers. However, a heat pump will operate at higher levels of coincidence, particularly under cold weather conditions. Hence large scale deployment of heat pumps will trigger the need to reinforce the distribution circuits although the trigger point for this will be dependent on the level of spare capacity and the number or the clustering of heat pumps connected.

There is some scope for demand side management using building preheating to manage peak demand but this would require significant volumes of household heat storage to have much impact.

The time taken to reinforce a distribution circuit is dependent on a number of factors and would vary significantly depending on the circuit to be reinforced but typically it might take a month (20 working days) to complete. This is equivalent to 0.2 work days per household. So if 10 million households had a heat pump installed, all of which requiring the distribution circuit to be reinforced, then this would take 2 million work days or over 5,000 work years to complete. For example, the timescale needed to deliver by 2050 would require 200 dedicated circuit reinforcing teams working continuously from 2025 onwards. This is appropriate where there is a high level of clustering, although at lower penetration levels on a limited number of circuits, there may be sufficient spare capacity to enable reinforcement to be avoided.

(N.B. These time and cost estimates cover only the distribution system – potentially consequential upgrades in capacity would be needed for generation and transmission. In many cases, the heat distribution system in the house would also have to be replaced to provide sufficient warmth at lower operating temperatures than previous gas systems would have produced.)

11.3 Heat – UK experience

The interview was held with Simon Woodward of Woodward Energy Consultancy. He was formerly the Chief Executive of Utilicom/Cofely District Energy for 20 years. In 2014 he left to set up in independent private practice as Woodward Energy Consulting. He was instrumental in the formation of the UK District Energy Association and is the current Chairman and Technical Director.

The importance was stressed of recognising that district heat network construction is currently a “cottage industry” in the UK, with little more than 100km of heat network constructed annually. Installing heat networks is a lot more challenging than electricity cables - the pipework needs to be steel and as a result the circuits must be pre-stressed and expansion joints installed at regular intervals. Installation would use open trench techniques and would pose major challenges, particularly in highly congested urban areas.

It was also emphasised that the industry is at a significant disadvantage compared to gas and electricity networks as it is not regulated and has no statutory rights for wayleaves and easements. Consequently, financing is complex and expensive, and planning can be lengthy.

Substantial increases in construction capacity would be required to enable district heating to be deployed on any large scale and this is unlikely to happen without considerable support and commitment from government/local authorities. If this is not forthcoming district heating will probably remain a niche heating technology with a market penetration by 2050 towards the lower end of Government projections, i.e. circa 10%.

11.4 Heat – Danish experience

The interviews were held with Birger Lauersen and Anders Brix Thomson. Birger Lauersen is International Affairs Manager of the Danish District Heating Association. He has worked for them since 1994, initially as an economic advisor dealing with energy taxation, regulation, heat purchase contracts and a host other matters, and from 1998 also with responsibility for international affairs. Anders Thomson is with the Danish Energy Association and has considerable experience in heat planning for Greater Copenhagen, as well as being Climate and Energy Coordinator for the city. He has also managed projects in areas of energy planning, including heat supply for the Nordhavn development; the provision of large heat pumps in heat networks; analysis of the supply of heat to new low-energy use urban extensions; and economic analysis and planning for the use of biogas in the municipality.

District heat networks were rolled out in Denmark mostly during the 80s and 90s and more recently are being introduced to areas of lower heat density. Typically, 10,000 to 15,000 buildings are converted each year from gas to district heating. These are mostly larger detached houses in less congested areas. The challenge for the large scale deployment is not so much technical but much more planning/ organisational. Public and local support is critical to the successful deployment of district heating - this is especially important as disruption can be significant. Impact assessments need to include socio-economic investigations.

Heat network installation costs can vary significantly and detailed site specific surveys are essential. In dense urban areas tunnelling has been used where trenching is not possible. Storage is particularly important and there are currently a number of very large seasonal storage facilities under construction, integrated with a number of heat sources.

It was noted that it would take time for the UK to develop the capability and capacity for large scale deployment but that the technology was well proven and existing skills could be readily adapted. It was noted that, in Denmark, there had been a lull in heat development, and that this meant that the resources were not readily available to address the recent resurgence in district heating demand arising from the urban sustainability planning approach adopted by the Danish Government.

11.5 Gas

The interview was held with Dan Sadler, Head of Energy Futures, Northern Gas Networks. Dan has worked in the gas industry for over 15 years. He is currently responsible for the H21 Leeds Citygate project which is to produce a design scenario for the conversion of the Leeds gas network from natural gas to hydrogen. The project will provide a design for the gas network in Leeds covering a high pressure (17 bar) outer city ring main transporting methane (natural gas), strategically placed steam methane reforming (SMR) plants and the necessary connections into the existing < 7 bar distribution network and includes the conversion of household appliances from methane to hydrogen.

This would build on the company’s previous experience of the practical problems encountered when installing pipes in dense urban areas. These range from traffic management, with road closures and the need to liaise with the local authority, through to the technical challenges associated with routing the pipes around obstacles and other utility infrastructure. For large future developments, particularly those associated with district heating which require two large pipes, it may be necessary to use deep burial or tunnelling for the combined networks, which would add very significantly to the cost.

Repurposing the gas network for hydrogen removes the need for street works as most of it will have already been replaced or targeted for replacement with polyethylene pipe as part of the Iron Main Replacement Programme, which was agreed with the Health and Safety Executive for safety reasons[17].

There are currently two main options for hydrogen production – electrolysis of water which is expensive due to the costs of electricity and which would require additional capacity to make a significant contribution to heat demand, or the production from natural gas using Steam Methane Reformation technology where the viability is dependent on CCS.

The work required to changeover households from natural gas to hydrogen is very different to electricity or district heat as little is required in the network itself. Instead, each household would need to have its gas installation inspected to identify any gas appliances that would need to be converted and any other issues that might need attention. Typically, an area for changeover would comprise 2,500 households and might take a month (20 working days) to complete. This is equivalent to 8 workdays per thousand households. So if, for example, 10 million households were to changeover from natural gas to hydrogen then this would take 80 thousand work days or about 200 work years.

On this basis, to complete a programme by 2050 would require 8 dedicated conversion teams working continuously from 2025 onwards to convert the remaining 10 million households. (NB the conversion from town gas to natural gas in the 1960s/70s took approximately 10 years and involved the conversion of 40 million appliances).

11.6 Summary and conclusions from interviews

Retrofitting networks in dense urban areas will be technically and logistically challenging as well as expensive and will require considerable planning and organisation. Repurposing gas networks for hydrogen avoids the need for street works, and household conversion can be implemented much more quickly than for electricity or district heat. However, its viability as an option is dependent on the availability of affordable and high volume low carbon sources of hydrogen which will require a major cost

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[17] Health and Safety Executive. "Enforcement policy for the replacement of iron mains risk reduction programme 2013-2021.

reduction and significant new generating capacity for electrolysis, or be dependent on CCS for the conversion of natural gas to hydrogen.

Electricity networks will need to be reinforced for the large scale deployment of electric heat pumps and the scale required will be dependent not just on the number of heat pumps deployed but also the extent of clustering on individual circuits. Demand side management, using preheating to manage peak demand would require significant volumes of household water storage to have much impact. For the large scale deployment of electric heat pumps the resources and timescales required would be considerable.

District heating is little more than a “cottage industry” in the UK and a substantial investment and a period of mobilisation would be required to enable networks to be deployed at scale. They are also at a significant disadvantage to gas and electricity networks, as they are not regulated and have no statutory rights for way leaves and easements. Consequently, financing is complex and expensive.

12. Annex E - Advisory Board members

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Tony Glover, Energy Networks Association

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13. Report supplement: Infrastructure transitions - a review of the evidence

This section reviews current national and international efforts in a range of areas relating to large-scale infrastructure transitions. It focuses in particular on examples of comparable past and previous transitions, recent and ongoing studies in the field of infrastructure transitions, options for gas grid decarbonisation, issues around the management of peak heat demand, options for low carbon heat generation within heat networks and the mass rollout of heat pumps and heat networks.

13.1 Transitions theory

In recent years there appears to have been a growing interest in the use of historical examples of transitions as a means of testing and elucidating the theoretical explanations of how transitions come about (Foxon et al., 2010; Hirsch and Jones, 2014; Shackley and Green, 2007; Verbong and Geels, 2007). Geels (2002) presents the example of the shift from sailing ships to steamships within the conceptual framework of the 'multi-level perspective', in which cumulative 'niche' technological changes (as well as change in the concomitant social framework: industrial networks, regulation, cultural norms etc.) are able to break through and challenge the dominant 'regime' when changes at the 'landscape' level – perhaps political or economic upheavals – present a window of opportunity. For example, one such case study presents the transition from horse-drawn carriages to automobiles, arguing that the triumph of gasoline over steam and electric propulsion was more than linear technological substitution, having benefited from niche exploitation and the dealignment and realignment of socio-technical elements at each of the three levels (Geels, 2005a). Other historical cases cited include the move from propeller-piston engines to turbojets (Geels, 2005b), and the provision of public water and sewage systems (Söderholm, 2013). Some papers advocate looking back through history in order to support policy-making today, to avoid repeating past mistakes and to understand the extent and nature of the demands that a low carbon transition would impose (Hirsch and Jones, 2014; Pearson and Foxon, 2012).

The literature frequently discusses the macro-level social and economic trends that precede and follow transitions such as those from biomass to coal, coal to oil and oil to gas. For example, the prices of various energy forms in relation to one another and to capital and labour, the public health drives of the nineteenth and early twentieth centuries and the direction of the dominant intellectual tides of the time (Energy Policy [Editorial], 2012). Insight into past energy transitions has highlighted the important role that novel end-use technologies play in driving the demand for new energy sources, the generally slow pace at which they occur and the common pattern by which energy technologies, initially costly and imperfect, undergo dramatic periods of growth, driving the transition on further (Grübler, 2012). They also highlight the reaction of incumbents to threats to their business models. These 'last gasp' efforts to respond to new competitive pressures can take the form of rapid technological innovation – such as late improvements made to sailing vessels when steam ships appeared, and the invention of the gas mantle in response to electric lighting – or as outright resistance, as seen in the response of German utilities to the introduction of the feed-in tariff in the 1990s. Which response occurs is likely to be determined in part by the origin of the 'threat': i.e. is it a market threat or policy threat? Technologies can also disappear entirely, as with the canal network, which was often bought up by rail companies, used to build new lines and then closed (Pearson, 2013).

There appears to be very scant literature on past technological transitions that have been attempted but ultimately failed. Research on this topic could prove a useful and insightful counterpoint to the study of technology emergence and successful transitions. It is possible to speculate that the causes of transition failure could include rapid market changes (either on the demand or the supply side), unreliable government commitment, underdeveloped or uneconomical technologies, or social resistance.

13.2 Non-UK transitions

Recent literature on large technical systems often discusses water infrastructure – i.e. the creation and evolution of water networks that meet societal needs and functions. Geels (2005c) again adopts the conceptual framework of the multi-level perspective to explore the cultural as well as technological drivers of the transition from surface water (e.g. streams, rivers, wells) to piped water in the Netherlands, observing that the spread of water networks was slower in existing urban areas than new neighbourhoods because of the costs of breaking up streets. Networks also only supplied areas with sufficient real or anticipated demand, and so connections to poorer communities were slow to materialise. However, for the most part, '[large technical systems] research has mainly focussed on the emergence and development of large technical systems. Much less attention has been given to the change from one system to another' (Geels, 2005a, p.446; see also Arapostathis et al., 2014).

Neumann et al. (2015) analyse the evolution of wastewater systems in order to identify principal drivers, as well as to reveal discrepancies between the speed with which these drivers can apply pressure to the system and its original intended lifespan. They note that unforeseen rapid changes rendered Zurich's wastewater treatment infrastructure inadequate for over 90% of the period from 1860 to 1986, and conclude by considering alternatives to the twin strategies of 'predict and provide' and 'muddling through'. It is argued that greater flexibility is critical: operational flexibility (the capacity to react to changing load conditions) allows a system to respond to changing load conditions efficiently; managerial flexibility (the ability to control demand levels) can relieve infrastructure systems of the requirement to provide enough capacity for worst case scenario load conditions; and the notion of structural flexibility, achieved through increased modularity, may have implications for future heat systems. 'Muddling through' may be satisfactory where infrastructure investment is incremental. However, where the required sums are substantial it may be necessary to invest sufficiently ahead of need and include the option value of certain network configurations in order not to disallow future system flexibility. De Graf and van der Brugge (2010) raise the issue of timescale discrepancy, claiming Rotterdam's 'Watercity 2035' initiative provided a valuable policy niche which allowed innovative ideas to emerge separately from the mismatched policy and infrastructure renewal cycles, whilst van der Brugge (2004) claims that a transition has already occurred in Dutch water management: from a technocratic water engineering approach to 'integral and participatory' water management. This approach recognises the shifting complexity of the challenge and is pluralistic in its involvement of multiple stakeholders, as well as taking into account the social, ecological and physical elements of the water system. However, the question of what, if any, benefits this transition has delivered is not raised, and whilst the evaluations of different managerial approaches to complex infrastructure may be highly relevant to the issue of heat, no such studies emerged in this literature review.

Söderholm (2013) describes and compares two instances in which rural Swedish towns receive water infrastructure some decades apart – one before the establishment of a long term national plan for the provision of water services, the other after – and draws conclusions on the role of central governments in bringing about such transitions. The combined support of financial, legal and consultative measures provided and co-ordinated centrally appears to have achieved the goals of transition with a comprehensiveness that would otherwise have been unlikely. Financial backing and amended and supportive regulation reduced the risk to the local authority, as did the establishment of organisations capable of supplying technical expertise, spreading knowledge and co-ordinating activity at local, regional and national levels. Transitions are therefore likely to be challenging if the twin needs for both institutional change (e.g. changes to laws and cultural norms) and the requisite knowledge and expertise are not first addressed. Furthermore, there may be challenges associated with the operation of new systems – particularly at stress points and where future transformation or adaptation is required – in cases where the operator does not possess expertise accumulated through involvement in the construction process.

Ravens and Verbong (2007) discuss the Dutch experience with CHP. In the Netherlands combined heat and power (CHP) grew from producing 12% of electrical energy in 1968 to about 50% in 2003, although this growth did not follow a straightforward trajectory. CHP also met about 13% of total heat demand in 2003.

Attempts by the Dutch Government in the 1950s to integrate local and regional networks for manufactured gas met with opposition from the gas manufacturing industry, but after the discovery of large amounts of natural gas the country went through a state-guided transition to a nationwide transmission and distribution system, complete with the adaptation of end-use appliances. In 1974 the Dutch Government established a committee, with members drawn from the gas and electricity industry and scientific community, with the aim of investigating the potential for district heating and to support municipalities and regional authorities in decision making, but despite high initial expectations only 16 were built. A number of reasons have been put forward in attempts to explain this outcome. Firstly, gas distribution companies were owned by municipalities, who used profits from gas sales to finance municipal facilities, resulting in a clear disincentive to move away from sales of gas by the unit. Furthermore, CHP plants were established by electricity companies and competed with the incumbent system, leading to opposition from local authorities. Secondly, consumers were offered either gas for both heating and cooking, or heat and electricity supplied from a CHP plant. The latter proved unpopular because of unfamiliarity with electric cooking and an association of the collective provision of services with the practices of communist countries of the time. Thirdly, owing to a successful national programme of home insulation, the construction of smaller houses and delays in house building, demand was lower than expected, leading to financial problems. In the 1980s, interest from the Dutch national government in the energy saving potential of CHP led to a number of measures designed to promote it. These included the relaxing of previous rules regulating its use for industrial applications, the establishment of an organisation bringing together industrial actors and energy companies, and investment grants and preferential gas pricing for CHP. Further financial incentives for producers and consumers encouraged CHP, and utility consolidation brought together gas and electricity companies, reducing and eliminating opposition to heat networks from gas suppliers. CHP was sufficiently embedded by the 1990s to survive the removal of subsidies and the liberalisation of Dutch energy markets in the late 1990s and beyond, and the policy shift towards low carbon generation has led to an emerging interest in the potential of decentralised CHP.

The question of why the growth of heat networks in the UK has remained ‘small-scale, fragmented and hence technically sub-optimal’ is addressed with reference to the markets of Norway and the Netherlands by Hawkey and Webb (2014), these countries having been selected as case studies partly on the basis that both were early movers in the liberalisation of energy markets. Little is known about the political and economic governance institutions needed to support the emergence of district heating and cooling in this context. For example, their implementation in Denmark and Sweden took place prior to market liberalisation and was in most cases led by public authorities at one level or another. ‘The political and economic institutions characteristic of [co-ordinated market economies] are argued to result in greater capacity for sustainable energy development than those in [liberal market economies], because they create the necessary social infrastructure for cross-sectoral planning and deliberative problem-solving which is discouraged on grounds of inefficiency in [liberal market economies]’ (p.7). The institutional and cultural differences between the UK on one hand and Norway and the Netherlands on the other might be expected to foster long-term trust, collaboration and information sharing in the latter two. Whilst local authority funding mechanisms are predominantly grant-based in the UK, municipalities in these countries have greater fiscal control and higher levels of involvement in local enterprise. Heat network development may have been more successful in the Norway and the Netherlands due to a) the presence of state co-ordination and b) co-ordination mechanisms by which national and local authorities can grant area-based concessions that sustain business confidence in the potential for expansion.

13.3 UK transitions

In their paper on the governance of transitions, Arapostathis et al. (2013) present two periods of transition in the UK gas industry, contrasting the roles of governance in both and considering its significance at critical 'branching points'. The first period of transition (1877-1914) was market-led and saw the use of manufactured gas expand from lighting, mainly in well-off areas, to include other end-use services such as cooking and heating, as well as the gradual connection of poorer neighbourhoods to the gas networks. It was achieved, with little or no government involvement, through a variety of innovations that acted to boost both customer numbers and demand per household, including the use of advertising, the hiring out of new gas appliances, the installation of prepayment meters, the use of gas mantles to improve lighting efficiency and even 'lady demons' – women who demonstrated how to use the new gas cookers.

In contrast, the move from town gas to natural gas (1948-1977) was state-led and centrally co-ordinated and took place against the backdrop of the post-war consensus. It represented a response to structural and strategic challenges that the industry as a whole was facing – namely fragmentation, competitive pressures and the high and rising prices of town gas feedstocks – as well as to technical concerns over how best to integrate the newly-discovered North Sea gas into the energy mix. A decision was taken to convert the country's 40 million appliances to natural gas over ten years, and marketing campaigns, training programmes and pilot conversion schemes helped reassure the public and legitimise the new fuel.

These two case studies are characterised by important differences: market-led vs. state-led, the prominence of the demand side as opposed to the supply side and the rationale for each, i.e. profit motives or policy motives. Concluding, it is argued that both transitions were underpinned by trust: firstly between consumers and gas providers in order to foster acceptance of new uses of gas, and secondly to legitimise the components of the new regime. In both cases this trust revolved around (i) the new technologies (ii) personal relationships (e.g. 'lady demons', appliance converters) and (iii) institutions, be they public or private. Similarly, other papers emphasise the important role that technical standards can play in facilitating gas network transitions (Egyedi and Spirco, 2011; Zachariah-Wolff et al., 2007).

The next big shift in heating transitions occurred in 2005 with the mandatory introduction of condensing boilers. Product standards were critical in shifting the market and these could not have happened without an existing condensing boiler market that was established in the previous decade, largely through government and energy supplier grant programmes. Training the workforce was a critical component and achieved relatively quickly (2 years) once the decision to have a standard was announced (in the 2003 White Paper).

In a follow-up paper, Arapostathis et al. (2014) widen the scope to provide a perspective on gas industry evolution between 1960 and 2010, arguing that system integration and governance patterns are closely linked at all levels – micro, meso and macro. The development of technical components required new forms of societal organisation and changing roles for existing actors. Vertical integration of the industry during the shift to natural gas was a powerful means of bringing together disparate networks, which could have important implications when considering the possibility of a 'patchwork' of low carbon heating technologies that is sometimes raised. A shift away from one highly-embedded technology may place increasing demands on governance systems and add significantly to energy industry complexity.

Recent experience of infrastructure transitions in the UK is limited to a few relatively small examples, one of which is the transition the Isle of Man made recently from liquefied petroleum gas (LPG) to natural gas. Although the UK mainland saw a move away from town gas between 1967 and 1977, the Isle of Man remained reliant on LPG before the conversion programme aiming to switch 15,000 customers to natural gas took place (Shaw and Baglow, 2012). The 8,000 customers who remained on LPG faced higher bills and a more limited choice of appliances, and Manx Gas was left with the prospect of high capital costs for the maintenance of the old LPG infrastructure. In 2011 the Manx Government approved an investment programme that would extend the reach of the gas networks and convert remaining LPG-run appliances.

Lessons learned from this undertaking related to the training and abilities of staff and communication with customers, as well as the various technical challenges. Training schemes for employees were fully accredited and local engineers were used in order to retain the skills on the island. There was stakeholder involvement throughout, a dedicated telephone contact point, and an information and education programme as well as a mobile customer support centre present when the conversion was being carried out in each area. One challenge was managing to access the large number of homes and businesses at a date and time not set by the customer. Further information was fed out through websites, local press and social media. It was also necessary to carry out a thorough survey in advance to identify existing appliance defects and separate them from the conversion, and also to ensure safety issues had been addressed, which entailed a long lead time for the project.

13.4 Ongoing infrastructure transition studies in the UK

This section describes current and recent work relating to infrastructure transitions in the UK.

13.4.1 Heat and the City

Heat and the City is a multi-disciplinary research programme http://www.heatandthecity.org.uk/that aims to address the neglect of heat networks for the provision of heating and hot water in buildings in the UK. Based at Edinburgh University, it is ‘centrally concerned with the policy knowledge and instruments required to support sustainable, affordable, energy-saving heating and thermal comfort’. The rationale for the work centres on the assumption that major change is more likely to originate at the ‘meso’ scale – between the macro and the ‘micro’ – and adopts a whole systems perspective, thus including local planners, businesses and residents, as well as energy, finance and legal experts. The research has included a number of workshops on issues including policy options and financing for district heating and led to the publication of numerous academic papers on local engagement, governance and finance as well as national and international case studies (Hawkey et al., 2013; Hawkey and Webb, 2014). A 2011 workshop brought together representatives of private companies, local authorities and the UK and Scottish governments and others to discuss leadership, business models, governance and identifying, enabling and financing decentralised energy projects.

> *‘The research aims for a comprehensive picture by situating urban practices in relation to economic and political structures for energy systems. We seek to understand the socio-technical networks which stimulate innovation, in the context of multi-level governance, uncertainties over energy policy, and mature centralised energy markets dominated by transnational corporations’* (Heat and the City, 2013).

13.4.2 Infrastructure Transitions Research Consortium

The aim of the Infrastructure Transitions Research Consortium (ITRC) is to develop and demonstrate a new generation of system simulation models and tools to inform the analysis, planning and design of national infrastructure (ITRC, n.d.). It brings together representatives from academia, industry, professional organisations, government departments and local authorities, NGOs and supranational bodies. It conducts UK-focused analysis in the fields of energy, transport, water, waste and information and communication technologies (ICT) and works with partners on a number of work streams to ‘provide a basis for cross-sectoral and long-term decision-making for infrastructure planning, design and operation’. The models the ITRC is developing will help to:

- Yield new methods for analysing performance, risks and interdependencies
- Provide a virtual environment in which to test strategies for long-term investment
- Understand how alternative strategies perform under constraints such as reliability and security of supply, cost, carbon emissions, and adaptability to demographic and climate change
- Develop risk analysis models to test the ability of national infrastructure to withstand extreme weather shock events, and so inform long-term risk assessment and adaptation planning

ITRC has worked with organisations such as Infrastructure UK, Network Rail and National Grid to develop tools to support investment decision and identify and prepare for large-scale future trends, emerging technologies and climate impacts. It also includes the Major Infrastructure Tracking Unit, which was designed to monitor progress and address obstacles to infrastructure delivery. The Treasury published its *National Infrastructure Plan 2014* in December last year, which featured a discussion around infrastructure challenges – including skills, planning, consenting, resilience, cross-sectoral working and interdependencies – although contained only two mentions of heat (once saying that it should be affordable for homes and business, and a second time noting that gas demand will remain significant for some time to come). It does refer to some of the practical considerations that underpin infrastructure development, however, such as improving procurement and bolstering supply chain productivity and skills, and yet fails to discuss these in the context of heat (or wider) decarbonisation.

The ITRC research programme is based around five research questions: i) how can infrastructure capacity and demand be balanced in an uncertain future? ii) what are the risks of infrastructure failure, and how can we make it more resilient? iii) how do infrastructure systems evolve and interact with society and the economy? iv) what tools and methods are required? v) what should the UK's strategy be for integrated provision of national infrastructure in the long term?

Workstream 3 seeks to explore various approaches to simulating and interpreting the interactions between infrastructure, society and the economy in order to develop better models techniques for the future. These include: a framework for the spatial coupling of demand and supply to model the co-evolution of infrastructure provision and socio-demographic change; combining techniques from evolutionary economic to explore the relationship between infrastructure and the economy; a network dynamics approach to simulate infrastructure networks in the presence of various external driver; and developing methods to identify patterns of emergence.

Outputs from ITRC work include technical notes, reports and papers, including quantified heat scenarios to 2050 and a discussion around future heat uncertainties (particularly in cases where peak heating demand is met with electric heat pumps).

13.4.3 Transition Pathways to a Low Carbon Economy and Realising Transition Pathways

Established in 2008, the Transition Pathways to a Low Carbon Economy consortium was sponsored by E.On and EPSRC and includes a number of universities. 2012-2016 sees the continuation of the project under the second phase, known as Realising Transition Pathways.

Transitions Pathways to a Low Carbon Economy brought together engineers, social scientsts and policy analysts to develop three pathways towards a low carbon electricity system, each one of which is dominated by a different set of governance 'framings': either markets, government or civil society – each of which have a unique mix of technologies, institutional architecture and societal drivers (RTP Engine Room, 2015; Foxon, 2013).

Realising Transition Pathways extends this work by asking what needs to be done in order to bring about a successful transition to a low carbon electricity system. It will include horizon scanning for innovative technologies, demand response feasibility, uncertainties in economic analysis and estimated costs of investment requirements. It aims to contribute to thinking and decision-making around governance and regulation in a low carbon transition and will conclude in 2016.

13.5 Ongoing infrastructure transition studies in Europe

This section describes current and recent work relating to infrastructure transitions in northern Europe, in particular the Netherlands.

13.5.1 Energiesprong

Energieprong is not an academic study - it is using an approach similar to the 'action research' method, by which researchers simultaneously carry out research into a process and apply it to achieving a practical outcome. Energiesprong is a Dutch initiative that has brokered a deal between housing associations and builders to refurbish 110,000 local authority homes to 'net zero energy levels' – i.e. houses consume no more energy than they produce. It fills the role of an independent actor that drives and co-ordinates stakeholders to develop all parts of the housing refurbishment market in parallel.

Similar to the UK's Green Deal, the renovations are refurbished through future savings on energy bills and residents pay utility bills to the housing association instead of energy suppliers. Refurbishments are executed within ten days and buildings receive a 30-year energy performance guarantee (Energiesprong, n.d.).

The scheme is based around securing a large amount of demand for the product and negotiating favourable funding and regulation with financers and authorities, effectively reducing the risk for all parties, including the construction sector. Energiesprong is currently taking these ideas into the private homeowner sector through a deal with 175 parties that is intended to align the market conditions for this housing segment. The consortium is now making moves into British and French housing markets and, after going quiet for a while, it was announced early in November 2015 that it would receive sufficient funding to retrofit 5000 houses – only 5% of its original plan. There are currently no evaluation-style reports detailing the challenges and successes experienced by Energiesprong throughout this process, although these may emerge at a later date.

13.5.2 STRATEGO

The Stratego project is a European co-funded project developed within the framework of the Intelligent Energy Europe Programme. It works across 12 countries and has the following objectives:

- Provide tangible support in developing national heating and cooling plans
- Assist local authorities in evaluating their heating and cooling potential
- Find their priority area for intervention
- Identify local authority concrete projects that should be implemented

The project is therefore designed primarily to bring about real-world changes in heating and cooling at multiple levels, although with an emphasis on local authorities. The eight countries upon which Stratego focuses are Austria, Belgium, Croatia, the Czech Republic, Germany, Italy, Romania and the UK, with support coming from experienced partners in Denmark and Sweden and transferability outside target countries coming from the involvement of Spain and Poland.

Project outputs include the development of a Europe-wide 'thermal atlas' and the assessment of energy efficiency for five countries (including the UK); support for at least 23 cities and regions in mapping the potential for energy interventions; the provision of coaching for cities and regions and meetings with national authorities responsible for drafting heating and cooling plans. A report will be produced on areas of priority which will have been identified through the thermal atlas, and a small number of projects will be developed in these areas in collaboration with local authorities.

A core element of Stratego is the linking of national and subnational (i.e. city or regional level) authorities. The first phase of the work will prepare the ground for ambitious and coherent national level heating and cooling plans by providing key information to national authorities on the potential for energy efficiency. The second phase will support local authorities as they assess their own heating and cooling needs.

The project results are yet to be published but may contain useful lessons for this work.

13.5.3 Sustainability Transitions Research Network

Whilst not a study in and of itself, the Sustainability Transitions Research Network (STRN) was established in recent years in recognition of the increasing number of national studies carrying out research in the field of transitions governance, and devised as a means of sharing the knowledge generated. Incorporating transitions research in areas such as energy, mobility, housing, agriculture, water and the built environment, the work is built around themes that include 'governance, power and politics' and 'implementation strategies'.

There are around 20 'associated projects' listed on STRN's website, including 'Institutional analysis of technological innovation systems: the case of biogas' and international research underway in Iran, India and Thailand, although none of these relate directly to heat or heat infrastructure.

13.5.4 Governance of Urban Sustainability Transitions

With origins in smart homes research, 'urban living labs' are sites in cities such as buildings, streets and districts that have been 'devised to design, test and learn from social and technical innovation in real time'. Many urban living labs have been established across Europe, often using an action research approach to bring together partners for the co-creation of better products and services, and several have environmental benefits as an important component. For example, the Coventry City Lab aims to support users to develop and test innovations in low carbon vehicles; others count improved energy efficiency, increased public transport usage and biogas financing among their objectives (the latter in Switzerland).

However, none address large-scale infrastructure transitions, and whilst many have been established, and individual cases studied, their impact in different national contexts has yet to be systematically evaluated. Co-ordinated by Lund University and with Durham University, the Dutch Research Institute for Transitions (DRIFT) and Joanneum Research in Austria as partners, the Governance of Urban Sustainability Transitions (GUST) aims to develop a framework to evaluate urban living labs.

13.5.5 Transition Patterns Enabling Smart Energy Systems

The Dutch Research Institute for Transitions is also involved in a number of research and advisory projects with the public and private sectors, on topics such as inland waterways, the bioeconomy, urban sustainability and smart energy systems, as well as healthcare and social housing.

DRIFT is currently running a project known as TRAPESES (Transition Patterns Enabling Smart Energy Systems) with the Economics of Infrastructure Section at Delft University of Technology and grid operator Alliander, which seeks to understand the nature of the energy transitions in the Netherlands, in particular the 'tensions and synergies that arise between existing organisations and structures and new parties and developments influencing the future energy system' (DRIFT, 2015). There is special interest in what happens when top-down and bottom-up and innovations 'meet', and the possible challenges and opportunities for developing smart energy systems along the least disruptive transitions patterns

13.5.6 The Fundamental Transition Programme

The Knowledge Network for Systems Innovations and Transitions (KSI), based at Erasmus University in Rotterdam, has a 'fundamental transitions programme' which is divided into three research themes: i) historical transitions ii) current and future transitions and iii) governance of transitions and system innovations. It brings together over 80 researchers from around the world with an interest in transitions and systems innovation. The work has a strongly interdisciplinary attitude and aims to improve understanding of how transitions in energy, agriculture, transport and healthcare, for example, can be influenced. The network itself aims to address a second fundamental issue: the lack of diffusion of knowledge about transitions.

13.6 Ongoing infrastructure transition studies elsewhere

13.6.1 Transitioning of Urban Infrastructure Systems in the City of the Future

Research at the University of South Florida aims to develop various methods and techniques for long term urban infrastructure transitions, including a transitioning model, a multi-objective optimisation tools and a spatial decision support system. It is envisioned that these models will ‘permit all stakeholders in cities to explore effectively the benefits or disadvantages of alternative strategies during and after transition’ and explore social and economic dimensions in addition to technological and environmental aspects (USF, n.d.).

13.7 Options for decarbonising the gas grid

Under a 2050 scenario in which carbon constraints mean that natural gas plays no role in domestic heating, heat provision in the UK may consist of a much more diverse set of technologies: heat networks, electric heating and heat pumps could all play a role. Nevertheless, current distribution networks will almost certainly still exist and may play a strong part in the decarbonisation of heat – perhaps through its use as a carrier of biogas or of carbon dioxide intended for sequestration (DECC, 2013a). Discussion of the extent to which gas networks can be decarbonised largely concentrates on the role of hydrogen and biomass, with the potential for either varying depending on the use of carbon capture and storage technologies.

13.7.1 Biogas

Biogas is composed mainly of methane and carbon dioxide and is a product of the process of anaerobic digestion, whereby organic matter decomposes in the absence of oxygen. Feedstocks for the manufacture of biogas include animal slurries, municipal solid wastes, agricultural residues, energy crops and sewage. It can be burnt to produce electricity and heat and is most commonly used as fuel for boilers and electricity generators but it can also be upgraded to biomethane and injected into the natural gas grid, provided it meets certain criteria. The first injection facilities for biomethane from sewage started operations in Didcot in 2010 (Environment & Energy Management, 2010).

Modelling undertaken for DECC suggests that restrictions on feedstock availability and technology cost will limit the growth of biogas both in terms of scale and application (i.e. on-farm and sites located close to existing networks). Biogas power-only and CHP, under which the administrative burden of exporting heat can be averted, is predicted to see continued growth, reaching 23-37TWh by 2030 (SKM Enviros, 2011). The 2012 *Bioenergy Strategy* lowers this forecast, and suggests that whilst the injection of biomethane into the UK gas network may play a small role in the short term, it is unlikely there will be sufficient quantities of feedstock available to replace all the natural gas in the grid. ‘Some of the recent modelling runs predict around 20TWh of biogas from total gas demand of around 550TWh could be blended into the gas network in 2050 from the gasification of biomass, anaerobic digestion and landfill gas’ (DECC, 2012a, p.105). These estimates are equivalent to 3.6-6.7% of total annual gas demand. The technology is also still in a developmental stage, although the number of biomethane-to-grid facilities is growing steadily (Gas International, 2013; GreenGas, 2015). In the medium term, there may be scope for synthetic biogas (discussed below).

Under the correct quality and composition, existing infrastructure and appliances (and natural gas vehicles) would be able to operate on biomethane, reducing the amount and extent of disruptive change that might be required under alternative heat decarbonisation scenarios. The technology faces various technical, economic and legal hurdles, as well as those presented by the current regulatory regime, which was designed without biomethane in mind, and which controls the quality and composition of the fuel.

Whereas the grid has been constructed on the basis that gas is transported through high pressure transmission pipelines to the lower-pressure distribution networks and service pipes which supply homes and business, biomethane producers are likely to wish to connect at the distribution end of the system. This raises questions around whether low pressure networks can accommodate this, how much investment would be required and how the quality of the biomethane entering the system can be assured (Ofgem, 2011). The lower calorific value of biomethane compared to natural gas calls for blending with conventional gas or the addition of propane in order to ensure that the energy content per unit of volume matches that of the rest of the gas system. Storage of biomethane, which is produced at a relatively constant rate all year round, is currently uneconomical, meaning that at present it is unable to contribute significantly to meeting periods of peak demand in winter. Other technical considerations include the physical conditions of the gas in the pipelines (flow rate, pressure, temperature and composition) and the possible presence of 'sensitive installations' downstream of the injection point (chemical companies, gas power plants etc.) (entsog, 2011).

13.7.2 Hydrogen

Hydrogen can be combusted directly – as it was prior to the switch to natural gas, when it accounted for around 50% of town gas – or it can be used in fuel cells. Its applications include domestic heating, industrial processes and transport, although the steady integration of heating and transport into the electricity system could see the introduction of hydrogen as an alternative vector used to increase system-wide flexibility. Fuel cells can be highly efficient but produce local emissions when powered by natural gas (for example, through the existing distribution networks). The UK Hydrogen and Fuel Cell Association has estimated that if fuel cell micro-CHP units replaced conventional household gas boilers, household emissions could fall by 40-50% (IGEM, 2012). Current UK production is around 7.6bn Nm^3 a year from 15 or so sites, of which almost half is a by-product coming mostly from the chemical industry (Heap, forthcoming). Most hydrogen is currently produced though steam reformation powered by fossil fuels – typically natural gas – but a small proportion comes from a variety of other methods, including biomass gasification and electrolysis of water. It is a crucial component in the manufacture of fertilisers and has applications in a range of petrochemical processes. Whilst modelling has been carried out that suggests a potential role for hydrogen as a source of heat for both buildings and industry, further work will be necessary to understand fully the associated costs and benefits (DECC, 2013a). One UK study raised concerns over the reduced capacity of linepack storage – gas effectively 'stored' within the pipelines – and the need to fit new meters as part of a large-scale hydrogen conversion programme (Dodds and Demoullin, 2013).

Pipelines for hydrogen are less well developed in the UK than in countries such as Canada, China and Thailand, but it may be possible to transport it through existing gas distribution networks: as pure hydrogen, as a low concentration blend with natural gas, or combined with carbon dioxide to form methane. A US study claimed that at hydrogen concentrations of 5-15%, the delivery of blended natural gas through existing pipelines appears technically viable, and without increasing risks associated with the compatibility of end-use appliances, public safety or the durability or integrity of current infrastructure. The appropriate blend is likely to vary from one network to another and would require the introduction of extensive testing, monitoring and maintenance (Melaina et al., 2013). However, the GridGas project recommended that hydrogen blends should not initially exceed 3% (ITM Power et al., 2013 cited in Dodds and Hawkes, 2014). The costs of laying hydrogen pipelines are dependent on, for example, geographical consideration, the manner of installation, securing access to private land and so on, and can therefore be difficult to gauge accurately. However, on average they are estimated to be in the region of 10-20% more expensive than equivalent natural gas infrastructure (Dodds et al., 2015). Operational distribution costs are also high, with the energy required to pump hydrogen through pipelines estimated to be in the region of four and a half times higher than for natural gas per unit of delivered energy, and higher still in the case of transport by road, rail or sea (IEA Technology Essentials, 2007).

A number of European tests and pilot projects are ongoing, including: in Denmark with the aim of demonstrating the effect of long periods of hydrogen exposure on the gas system (Energinet, 2013); in France, to provide fuel for natural gas vehicles and testing hydrogen as a way of storing renewable energy (Engie, 2012); and in Germany, where hydrogen produced through electrolysis is part of a trial injecting hydrogen into the gas network (ITM Power, 2013).

Modelling by Dodds and McDowall (2013) suggests that the only cost-optimal solution for continuing to supply energy to households via the current gas network is its re-appropriation for hydrogen distribution, although these results are sensitive to the long-term wholesale price of gas. The direct substitution of hydrogen for natural gas would also require the replacement of end-use appliances on a scale similar to the conversion from town gas to natural gas several decades ago, and the safety risks are higher than for natural gas where hydrogen is used in the home owing to its odourless and invisible properties and faster combustion velocity (Dodds et al., 2015). Further challenges include the greater demand for hydrogen by volume from, for example, fuel cells units, the 20-30% lower energy carrying capacity of hydrogen, the greater ease with which hydrogen escapes from pipes than natural gas and perceptions of risk and the need for failsafe guarantees (Clefs CEA, 2005). Hydrogen ‘embrittlement’ – degradation of pipe material through exposure to the gas – can lead to leakages and catastrophic failure in both metal and non-metallic compounds. Although its causes are not well defined, factors known to influence the rate and severity include: hydrogen concentration, pressure, temperature, purity, nature of impurities, stress level, stress rate, metal composition, metal tensile strength, grain size, microstructure and heat treatment history. Despite these concerns, however, there is scant evidence to suggest that the existing low pressure gas network would suffer degradation as a result of hydrogen injection and none indicating that polyethylene pipes and fittings would be adversely affected. Concentrations below 10% have a minimal effect on flame profile; those in the region of 10-20% may require a process of identification and modification of appliances, particularly older one (Hodges et al., 2015).

13.7.3 Synthetic natural gas

Synthetic natural gas (SNG) can be produced from various fossil fuels as well as biofuels, in which case it is known as bio-SNG. SNG has a number of advantages, not least the availability of end-use technologies that are well developed – such as gas appliances, combined cycle turbines and even compressed natural gas vehicles – and a readymade distribution infrastructure (Kopyscinski et al., 2010). It can also be produced upon demand, being effectively ‘stored’ in the meantime, and is therefore well-suited to meet the requirements of the current fluctuating seasonal and diurnal demand levels. The physical characteristics of SNG can also be matched, during the production process or through blending, to those of the fuel it is replacing, ensuring a smooth shift from one to the other (Zwart et al., 2006). The efficiency with which feedstocks can be converted to SNG can also be high in relation to hydrogen and biogas production: roughly 60% using the steam-oxygen coal gasification process and up to 65% using hydrogasification and catalytic gasification, with the (theoretical) possibility of efficiency rates of 70-80%.

When using various feedstocks to produce SNG, their carbon content is first gasified and then converted to methane, the principal component (over 95%) of natural gas. The abundance of coal, its relatively low price and its widespread availability makes it an attractive fuel for many countries for reasons of energy security. The concept of producing SNG from biomass is relatively new and less proven than the use of coal, but it also presents the opportunity of negative emissions through the addition of carbon capture and storage. The coal-powered Great Plains SNG plant in the USA has been demonstrating carbon capture for a number of years, producing about 95 million cubic feet of carbon dioxide per day, which is then transported to Canada for use in enhanced oil recovery processes (Chandel and Williams, 2009). However, it has been plagued by economic difficulties and its local and regional environmental impact is substantial.

From the perspective of heat provision, the requirements of local biomass combustion, combined heat and power and electricity appear significantly more demanding than SNG, which does not require new power capacity or new equipment, and operates on a scale allowing greater efficiencies than local heat generation. The use of coal as a feedstock would certainly require carbon capture and storage in order to meet emissions legislation and, where biomass is used, the large quantity of feedstock required would also pose significant challenges. It has been estimated that the Netherlands, a relatively small country, would need to import around 20 million tonnes of biomass a year, which is considerable but not implausible (Zwart, n.d.).

SNG and bio-SNG are at varying stages of testing and trialling. National Grid and partners have won funding from Ofgem to build a demonstration plant for the gasification of mixed domestic and commercial waste and pure biomass feedstocks. This is intended to lead to the construction of a number of plants, injecting large quantities of renewable gas into the network (National Grid, n.d.). In Germany a power-to-gas plant uses surplus electricity from renewables to produce hydrogen from water which is then combined with carbon dioxide from a biogas plant to yield natural gas or methane, with the view of introducing it into the balancing energy market (Schmack, n.d.). Both of these processes are currently prohibitively expensive without the provision of financial support. From a network perspective, SNG – sufficiently 'cleaned', with as much carbon dioxide extracted as possible – can comply with the various thermodynamic and chemical quality standards. SNG for injection into the grid may also require further compression in order to achieve pressures higher than those of the pipeline at the injection point, and there is a procedure for acquiring authorisation from National Grid. However, from a technical point of view, once the correct quality standards have been reached, SNG is fully compatible for use within the existing gas infrastructure (E4tech, 2010).

13.8 Managing peak heat consumption patterns

Heat demand fluctuates throughout the day and across the seasons, with external temperature representing the strongest driver. Roughly equivalent peaks occur on a daily basis around 7am (8am at the weekends) and again around 6pm. Seasonal peaks occur during the colder months, and the difference between the demand peaks and troughs is considerably higher than those seen in electricity supply; winter demand can be five times greater than summertime levels (DECC, 2012b). In contrast, electricity demand goes up by around half in the winter months.

A number of reports have modelled future heat scenarios (e.g. Element Energy and AEA, 2012; Energy Technologies Institute, 2014; UKERC, 2013) – compared by Sansom (2014) – which offer a wide range of alternative futures for space and water heating technologies in 2050. For example, heat pump penetration is projected to be less than 30% or greater than 80%, and direct electric heating could be less than 5% or over 40% depending on the scenario in question. There is therefore a high degree of uncertainty around the share that will be taken by each technology, and although the scenarios are in agreement that heat pumps will play a significant role, there is little agreement around just how large this role might be.

Relatively little has been written on the management and reduction of peak demand in heating through the employment of energy efficiency (Langham et al., 2010). Discussing the advantages of networks, Raine et al. (2014) observe that connecting a number of buildings to a central heat source results in a smoother aggregate heat demand which is easier to match with supply. Separate peak demands are likely to occur at different times in different buildings and a larger centralised heating unit may benefit from economies of scale. Palmer et al. (2013) found in their study monitoring household electricity usage that only one third of households used any hot water at all at peak times and that the majority of these do so for showers – i.e. two thirds use no electricity for hot water or showers between 6pm and 7pm. The 15% of households within the study that use peak electricity for water heating may then be an appropriate target for attempts to shift this load away from peak times. Addressing the shower component of this peak electricity usage by changing people's washing habits may present more difficulties.

13.9 Energy efficiency

Over the last decade, energy demand for space heating has fallen substantially due primarily to improvements in fabric insulation and boiler efficiency, especially with the introduction of condensing technology to recover waste heat. Hence the challenge is to continue these improvements at reasonable cost particularly with the need to consider the efficacy of solid wall insulation which form 30% (7 million homes) of the UK's building stock.

The rebound effect (direct and indirect) is well-recognised in the literature on space heating, with the energy savings resulting from home insulation measures rarely reaching the theoretical projections (Greening et al., 2000; Sorrell, 2007). Existing gas boilers are generally on/off appliances (though not always – see below), which is to say they operate at maximum load until the set temperature has been reached, at which point they switch off. Factors that can influence the size of the peak load are therefore limited to the number of boilers running simultaneously and their individual capacities. Palmer (2012) recounts the relationship between energy efficiency measures and space heating demand in Melbourne over a 50-year period, using four scenarios to illustrate the relationship between energy efficiency and peak load on a winter day between 6:30am and 7:30am.

1. Inefficient building fabric leads to large overnight heat losses. The boiler needs to operate for a lengthy period from 6:30am to reach the desired temperature.
2. High quality materials reduce overnight heat loss, but the boiler still needs to run at 6:30 in the morning (albeit for a shorter duration) for the house to reach an acceptable temperature.
3. Heating is not required till later in the morning, so the boiler does not contribute to peak load.
4. The boiler is left cycling all night long, and so only contributes a small amount to the morning peak. Overall energy demand is higher, however, and any energy efficiency measures would have a negligible effect, i.e. an increase in overall demand causes a reduction in peak demand.

Plotting overnight minimum temperature against morning peak hourly gas consumption reveals that gas usage does not continue the upward trend as temperatures fall, instead flattening off (the relationship otherwise being one of negative correlation). Palmer observes that this could indicate saturation of gas consumption – effectively a large number of boilers operating at 100%. Were this the case, incremental improvements to household energy efficiency – i.e. a shift from case 1 to case 2, above – might reduce total energy use but would do little to reduce peak consumptions. On the other hand, a pilot study in Gothenburg forming part of a PhD has found that the fabric of residential buildings can store as much as 0.1kWh/m^2 with the internal temperature varying by no more than 0.5°C, and that this goes unnoticed by residents. This means that modest reductions in peak demand may be achieved by 'pre-heating' buildings in advance of anticipated peak periods (Chalmers, 2015).

One answer could be to reduce the capacity of boilers in use at peak time in order to spread the load over a longer timeframe, although it is claimed that 'slower' boilers tend to be seen less favourably by consumers. Whilst currently installed gas boilers typically cycle at full capacity until the desired temperature is reached, a new generation of variable capacity heating, ventilating and air conditioning units is emerging. An American study testing these new units found significant efficiency improvements over the older models and demonstrated reductions in peak demand for both heating and cooling of 21.5% and 22.7% respectively – higher when used in conjunction with indoor ducts (Cummings and Withers, 2014). Inverter-driven heat pumps also have more flexibility in how they operate, meaning that the impact on overall peak can be reduced. This is commonplace among air source heat pumps but most ground source heat pumps are still on/off models (DHPA, 2015).

In Norway, the requirement that new residential buildings be connected to a district heating network has been shown to be a barrier to construction, since developers favour the lower installation costs of electric heating, illustrating the need to be flexible in the face of unintended consequences. Thyholt and Hestnes (2008) demonstrate the reduced emissions seen in typical well-insulated Norwegian homes connected to district heating networks compared with those using electric heating, although they conclude that the difference is marginal when viewed over the long term. The impact on peak power demand is also likely to be marginal (considerably less than 5%). The potential of electric heat pumps operating in tandem with passive heat storage in buildings is thought to be substantially more cost-effective than storage by heat accumulation tanks (under a 50% wind generation scenario), as well as providing additional system flexibility benefits (Hedegaard et al., 2012).

13.10 Heat storage

The term 'sensible heat' refers to the change in temperature an object undergoes when heat is applied to or removed from it, e.g. water in a storage tank. It can be contrasted with 'latent heat', which describes the heat required for a substance to change state. For example, when heat is applied to ice the ice itself will remain at 0°C whilst melting; the heat therefore causes a change of state with no change in temperature. In latent heat storage systems, a material will undergo a change in phase – typically from solid to liquid – and is therefore known as a 'phase change material'. Systems using phase change materials for thermal storage are in relative infancy and face technical challenges including low thermal conductivity, achieving an energy storage density significantly better than water and reaching sufficiently high heat discharge rates. Thermochemical energy storage, which breaks material into two components and then recombines them to produce heat, is the least technologically developed heat storage option, although it offers benefits such as energy density, room temperature storage and little or no degradation in stored energy content.

Sensible heat storage is thus the most developed option at present, and the lion's share of technologies are based on this approach, including the four main types: tank thermal energy stores, pit thermal energy stores, borehole thermal energy stores and aquifer thermal energy stores. The question of whether or not to install heat storage is largely determined by whether or not the extra capital costs can be recouped at a later date, especially in the case of large-scale storage as with district heating. There is also a strong relationship between cost and size, with small tank storage systems costing around £390/m^3 and pit storage with a volume of 75,000m^3 falling to approximately £25/m^3. In a district heating context, a thermal energy store can be used to even out fluctuations in demand, allowing the plant to run more evenly and therefore more efficiently. In the case of the Pimlico District Heating Undertaking (1950s) the 2500m^3 water-based thermal energy store provides short-term system balancing for a heat network supplying 3256 home, 50 businesses and three schools.

Tank size is a critical issue for residential heat storage. The size of the storage tank required depends on the energy efficiency of the house, with a 2.6m^3 tank needed to provide water-based thermal storage for an average property built to 1980s regulations and a much smaller 0.56m^3 tank required for one built to 2010 specifications. Storage based on phase change materials, in conjunction with an energy efficiency refurbishment to bring the property up to current standards and a heat pump, would require a tank of 187 litres (0.187m^3). This is less than the volume of the hot water tanks removed from many homes but whether householders are willing and able to sacrifice the new-found space is unclear. In addition, the abolition of the Green Deal may add to the challenge of retrofitting huge numbers of homes. Nevertheless, 'this type of system has the potential to support domestic energy demand reduction whilst at the same time minimising supply challenges for the electricity utilities' (Eames et al., 2014, p.35).

ITM Power (2015) cites grid balancing difficulties that can occur when wind generation accounts for 20% of peak capacity. Power-to-gas and associated storage technologies present an alternative to the growing solution of curtailment and has an advantage over other types of storage due to the potentially large capacity and greater discharge time, as well as the value it may add to both electricity and gas grids. The Energy Technologies Institute (2015) has investigated the potential for greatly expanding the storage of hydrogen in salt caverns to contribute to the meeting of daily electricity peaks, which it estimates has the potential to provide tens of GW to the electricity grid on a load-following basis from hydrogen turbines, although the 'round trip' efficiency is just 40-50%. This is roughly equivalent to compressed air energy storage (55%) but compares poorly with pumped storage (75-85%), although costs are predicted to fall over the coming decade (Heap, forthcoming). An electrolyser captures excess power (such as from wind farms) to produce hydrogen, which can then be stored until required for electricity generation or, once stores are full, injected into the gas grid as an overflow, for example. This is predicted to add value at lower loads (and certainly below 40%), and the ETI's modelling shows hydrogen caverns under construction from 2030, with gas prices largely determining the point at which stored hydrogen becomes preferable to other modes of generation. Onshore sites are likely to be considerably less expensive than those found offshore. The ETI estimates that a 300,000m^3 'fast fill' cavern in Yorkshire could cost around £200m.

13.11 Mass heat pump development

Experience of widespread heat pump installation, either at local or national level, appears to be limited, although several studies consider decarbonisation pathways that take into account the integration of large numbers of heat pumps into the energy system (e.g. Leveque and Robertson, 2010; HHIC, 2015; Delta Energy & Environment, 2012). This includes the potential for a greater amount of demand side flexibility, the accommodation of higher amounts of variable generation and the impacts of greater loads of the electricity system (Papaefthymiou et al., 2012; Arteconi et al., 2013; Buckett, 2007). Scenarios in which energy and carbon targets are met whilst cost is minimised frequently cite the electrification of heat as a critical component, although this introduces challenges such as the management of power flow and the meeting of winter peaks (Spiers et al., 2010). These changes would entail significant practical challenges for electricity distribution infrastructure, due partly to the level of uncertainty around, for example, continuously fluctuating load profiles and the lack of fine-grained demand data, loads that are unbalanced between the three phases, and a poor understanding of the locations and connections of physical (often buried) infrastructure. It may be possible to draw lessons from the experience of upgrading low voltage networks to accommodate the growing electrification of space heating several decades ago.

As with district heating, northern European countries have witnessed the highest levels of heat pump installation, including Sweden and Switzerland, which have had supportive policies in place for decades – even during and after the market collapse of the 1980s. A review of the successes of these countries in developing and commercialising heat pump technologies reveals a number of now-familiar issues and requirements. For example, support policies must be continuous and long-term yet also flexible, they ought to be system-orientated and consider the evolution of the wider energy system and credible testing and certification procedures are essential (Grübler et al., 2012; Buckett, 2007) – findings supported by UK studies (Frontier Economics, 2013). National difference in heating practices, substituted heat and primary electricity generation mix are pivotal (Bayer et al., 2012). The difference in take-up between the UK and other northern European countries can be attributed to factors including the reach and extent of the UK's gas networks, average seasonal temperatures, levels of government support, energy prices, the relative costs of heating technologies, housing characteristics and others. Fawcett (2010) cites a study showing that 90% of purchasers of ground source heat pumps are very happy with their system but that only 40% reported the anticipated cost savings, 20% found the controls very difficult to use and a quarter complained about the system's slow response time or its inability to heat the space to the required temperature (Roy et al., 2008).

Hannon (2015) contrasts the heating sectors of Finland and the UK and discusses whether the rise in heat pump use seen in Finland since 1970 (now standing at 18% of all homes) might be emulated here. 90% of the heating demand from residential, commercial and public buildings in Finland is met by district heating, with electricity and biomass both at 21%, oil at 11% and gas meeting only 1% of this demand. In the UK the domestic and service sectors' heat demand is met by gas (77%), electricity (12%), oil (7%), bioenergy and waste (2%), solid fuel (1%) and district heating (1%). When it comes to replicating the high rate of heat pump installation seen in Finland, several contextual factors cannot be transferred to the UK, among them the characteristics of the housing stock, which is generally much newer and more energy efficient, the much less well-developed gas distribution infrastructure, which limits customers' heating options, and the country's climate. A successful policy approach would need to bring together the renovation of the existing building stock, the adoption of high building efficiency standards, fiscal measures allowing heat pumps to compete with gas heating on a cost basis and the concentration of support on areas off the gas grid.

Addressing the lack of real-world data on heat pump performance, the Energy Saving Trust (2010) monitored 83 heat pumps in residential properties across Great Britain between April 2009 and March 2010, and examined the factors that influence system performance. The study found wide variation in the performance of heat pumps, and that well-designed and, crucially, well-installed systems can lead to both lifetime carbon savings and high levels of consumer satisfaction. Issues around system installation appear to be significant: earlier systems often experienced sub-optimal installation, and the more complex ones performed less efficiently. Likewise, customers often reported difficulty understanding the operating instructions. Together, these point towards the importance of establishing high quality training, standards, operating instructions and customer service (before, during and after installation). These lessons could be considered in the case of other low carbon technologies – heat or otherwise – and might be regarded as an essential governance element in decarbonisation undertakings. Phase 2 of the study explored the variation in performance identified in the first phase (Energy Saving Trust, 2013). Interventions including technical modifications and the provision of improved guidance material for consumers were carried out and the results monitored for a year. The findings demonstrated the potential of these (sometimes minor) interventions to lead to better performance, and revealed that technical improvements (for example, to design and installation) yield more significant improvements than changes in consumer behaviour. The interventions also led to an improvement in the perception of heat pumps among consumers participating in the study, underlining the potential of heat pumps and the importance of early positive consumer experiences.

13.12 Mass heat network development

Most international research and activity regarding heat transitions appears to be situated, unsurprisingly, in countries with colder climates and experience of district heating and heat pumps: Denmark (Lund at al., 2010; Østergaard et al., 2010; Østergaard and Lund, 2011), Norway (Thyholt and Hestnes, 2008), Finland (Hannon, 2015) and Sweden (Difs et al., 2009) are all cited in the literature.

In Denmark, where almost half of net heat demand is met by district heating, a number of modelled scenarios have been published in order to aid the analysis, design and implementation of future heat systems – often at a municipal level – although these tend to focus on technical, financial and environmental (i.e. emissions) details rather than governance issues (e.g. Persson and Werner, 2011). Lund et al. (2010) conclude that the optimum course for Denmark would be to continue the gradual expansion of district heating networks whilst installing heat pumps in areas remote from these. The country has also seen growth in the number of solar powered district heat networks.

A Swedish study found that the application of district heating to sparsely populated areas is likely to be possible under certain conditions, namely: where the density of and overall demand for heat is above a certain level, and where there are both low distribution costs and low marginal heat generation costs;

and in addition the high taxes placed on competing fuels in Sweden favours district heating in a way that may not apply to other countries (Reidhav and Werner, 2008). Also examining the issue of sparse district heating in Sweden, Nilsson et al. (2008) note the potential value of more active management of innovation in the sector, citing novel methods of trench excavation as an example, although the associated costs and greater time requirements may mean that innovation efforts might best be focused on rationalising construction processes and improving co-ordination between contractors.

Experience of installing district heating in the UK is far more limited than in these more northerly countries. A paper produced as part of the aforementioned Heat and the City project asks what constitutes a 'non-financial barrier' to the development of district heating, and highlights the key challenges a project developer would face (Heat and the City, n.d.). Heat networks possess characteristics much like other elements of energy infrastructure: they require a large amount of capital expenditure and provide a return over a period of time measured in decades, they rely on an enduring demand for the service they provide and they are long-lasting (or are at least built with that intention). In addition they provide a monopoly service, and consumers need to trust the operators to set a price perceived to be fair and heat networks may compete with other forms of energy supply, such as electricity, where that is a possibility.

The authors group these challenges into categories: i) embedding the network in the social and physical terrain ii) building experience and capacity iii) managing complexity and iv) assembling resources. The first refers to the need to embed district heating into a landscape dominated by electricity and gas networks. This landscape includes physical infrastructure, as well as the skills and expertise required for design and construction and the prevailing the policy and legal context and social norms and expectations. The second – building experience and capacity – can be understood as 'a lack of experience and an absence of routine procedures'. Developing a district heating scheme can be a relatively creative experience, since knowledge is often difficult to access and economic and technical best practices have yet to mature fully. Moreover, a lack of experience can create risk, or the perception of risk, and lead to additional costs. The expectations and objectives of collaborating actors may not be aligned and as well understood as they are with more conventional infrastructure projects. Thirdly, the inherent uncertainty in projects involving less mature technologies lends additional complexity to the work. This can take many forms: co-ordinating a wide range of parties, establishing the viability of a project, understanding the level and schedule of heat demand and interactions with existing energy markets can all add complications, but can also interact with one another as decision made in one area influence another. Finally, the resources required to achieve all this are significant right from the outset, with project development costs estimated to be around 10% of capital costs and risk therefore relatively high from early on. The human resources required may not be in the possession of the local authority (or lead developer) and so decisions may need to be taken as to how best to undertake the early scoping and data gathering and analysis steps. For example, is it best to develop in-house skills or to buy in the required expertise? This may also depend on longer-term strategic priorities, such as whether it is an aim to build up institutional reputation and expertise (as has occurred in Woking) or to alleviate fuel poverty and reduce carbon emissions, in which case developing skills may be less important.

King et al. (2011) detail the lessons that have been learnt through the practical experience of local authorities and developers across 13 case studies, which go some way towards addressing these challenges. Defining objectives clearly from the outset, and getting endorsement from all stakeholder, is essential, as is the need to guard against 'mission creep'. At this stage the importance of cost-effective financial and technical feasibility studies should not be underestimated. Local authorities in the 13 case studies found it beneficial to engage early with commercial energy market players in order to assess their suitability; for example large and small companies will each bring different advantages and disadvantages (expertise, flexibility, financial muscle etc.). In the same way the experience of other project partners in the case studies was found to vary widely, with some local authorities extending existing networks and others establishing entirely new ones. The latter had a generally low level of understanding of energy markets and less knowledge of the technical and feasibility processes required early on. This can lead to lengthy learning processes that draw out the length of the project, potentially raising risk and cost. Mirroring the experience of Woking Council, key players 'need to be involved early and at board level' in order to establish and maintain momentum – the role of champions is therefore critical. Given the various challenges identified above, it is likely that hurdles will appear throughout, and the lack of established procedures will mean that it will be necessary to engage creatively with the process to ensure there are no 'showstoppers'. Accessible legal and technical support were also seen as highly valuable.

In a document titled *Community Energy: Planning, Development and Delivery* (King and Shaw, 2010), the Combined Heat and Power Association provide planners and project developers with guidance to assist with the many facets of developing a community energy project from initiation to operation – primarily for CHP and district heating. This 'flightpath' comprises the following: objective setting, data gathering, project definition, options appraisal, feasibility study, financial modelling, business modelling, market testing, procurement and delivery. The guidelines contain examples of a variety of practical challenges that facing developers, including physical barriers such as railway lines, major road and rivers, and the establishment of a critical mass of demand. These emerge particularly as a result of the feasibility study and include the technical characteristics of the network, such as probably heat losses, pipe measurements and the potential for storage, but also the availability of land for the siting of the plant and the network pipes themselves. Whilst this document provides valuable guidance for planners and developers, it considers community energy only from a local perspective (for example, managing procurement processes) and does not raise challenges that may emerge when heat networks and CHP are scaled up substantially. These could include questions around the public acceptability of infrastructure works and associated disruption measured in decades instead of months and years, and whether or not supply chains are sufficiently strong to handle large increases in the demand for physical components.

Challenges relating to UK energy distribution infrastructure transitions in the context of decarbonisation are also discussed by Bolton and Foxon (2015). Addressing specifically the issue of city-scale district energy schemes, they observe that whilst strong local authority involvement has been a hallmark of the successful diffusion of district heating across Scandinavian countries, the powers of UK councils in energy planning have traditionally been more limited. It should be added that the powers and remit of local authorities have changed significantly since the days when municipal undertakings were strongly represented in electricity and gas supply, with a shift in responsibility from the *provision* to the *enabling* of energy services (Bulkeley and Kern, 2006 cited in Heat and the City, n.d.) as well as the constraints imposed by energy market liberalisation and state aid rules. A recent study carried out on behalf of the Department of Energy and Climate Change (DECC), identified a number of barriers to district heating, including: a lack of expertise and organisational capacity at a local level, a lack of upfront funding for the capital cost of laying pipes, uncertainty regarding longevity and reliability of customer demand, uncertainty regarding reliable heat sources, a lack of regulation, inconsistent heat pricing, a lack of generally accepted contract mechanisms, the lack of established roles for local authorities and skills gaps (BRE, 2013).

Organisational capacity in particular presents challenges for local authorities seeking to become involved in the sector, with many now-operational projects having been championed by motivated or knowledgeable individuals who co-ordinate and promote the enterprise. 'Securing a level of alignment between the technical (bottom up) and political (top down) processes have been key in successful schemes… "It's a combination of political and technical, managerial" requiring "strong political leadership and direction, managerial support and technical support. And if you can't get those three aligned it doesn't work"' (Bolton and Foxon, 2015, p.546). The lack of a supporting institutional framework means that system transitions are often reliant on these motivated individuals, and the wider diffusion of new technologies is likely to require institutions capable of spreading best practice and reducing transaction costs.

In enumerating some of the features of successful transitions Roelich et al. (2013) record similar observations: ‘One of the biggest challenges that case studies faced was aligning the interests of divergent actors. Once initial interests were aligned a key aspect of success was ensuring that actors derived benefit from participation’ (p.6). Although the authors seek a more theoretical understanding of the process of change, they cite several case studies, some of which are included below.

13.12.1 Olympic Park Energy Centre

London’s Olympic Park is powered by two ‘energy centres’, together forming the UK’s largest decentralised energy network and providing heating, cooling and power (46.5MW of heating and 16MW of cooling. The CHP units started operating in 2010 and were designed to accept different types of fuel to allow flexibility and capacity growth so that they could continue to supply the area into the future. Specifically, they are able to shift from natural gas to renewable synthetic gas as and when it becomes established.

As part of a large-scale urban development scheme in the run-up to the 2012 London Olympics it is likely to have faced a different set of challenges and potential benefits from those faced at other times and in other locations. For example, the Olympic Delivery Authority was able to specify that conventional heating systems were to be excluded from venues and buildings, thereby guaranteeing sufficient demand, as well as to ensure co-ordination and compatibility between primary and secondary heat networks. Furthermore, the advantages of having a ‘blank canvas’ to work with should not be underestimated (Maybank et al., 2011).

A central aim of the process was to provide infrastructure that would not then require the further re-laying of pipes and other utility services after the Games: ‘A high proportion of infrastructure cost is in design, labour, management and logistics, rather than the cost of materials; therefore, value for money was maximised by investing in larger cabling, pipe work and ducting for long-term use’ (Maybank et al., p.3). Specifically for the Stratford site, its rapid development under tight security was expected to add substantially to the overall cost. Certain restrictions were also placed on the project as a result of practicalities: insufficient space to accommodate a solid biomass boiler meant that the renewable generation element came from bio-oil (though ‘locally sourced’), and ideas for a biomass gasification facility were shelved due to the increased risk to private investors. More generally of importance for the installation of heat networks elsewhere, the lack of regulations for district heating pushed up the cost of the contracting process and meant that a specially commissioned contract was required, and the involvement of a large number of stakeholders added further complexity.

13.12.2 Woking Borough Council

Hawkey et al. (2013) present a number of case studies of the emergence of CHP with district heating and cooling to explore local energy governance and organisation models in the context of privatised and centralised energy markets, which have diminished the control of local authorities over energy provision. Woking’s strong involvement in district heating and cooling originated from environmental politics and interest in the potential of alternative technologies to reduce costs. The success of solar photovoltaic schemes and small-scale CHP systems in Woking in the 1990s strengthened political support for increasingly ambitious plans, including an assessment of the extent to which a local authority might provide energy services within its legal constraints. Thameswey, a commercial concern owned by the council, was created under instructions to act commercially and recycle its profits into environmental and energy services projects. Through Thameswey a joint venture was established with a Danish energy services company to develop and operate district heating and cooling systems and other energy initiatives.

In other locations where district heating systems operate, such as Aberdeen, they supply energy services principally to buildings under council control. In Woking, however, the mix of council and commercial customers introduce significant governance challenges, in particular the lengthy negotiation of tailored contracts with customers necessary in the absence of financial guarantees from the council. In addition, a lack of familiarity with the technology, the relatively small size of Thameswey and the lack of industry standards all contributed to increased perceptions of risk. Hawkey et al. (2013) conclude that the development of urban energy transformations 'in unsupportive circumstances requires forms of social capital which enable project developers to overcome the difficulties posed by delocalised investment finance' (p.17).

13.13 Options for low carbon heat generation with heat networks

A summary database compiled by the UK government (DECC, 2013b) takes the phrase 'heat network' to refer to either a) two or more buildings connected to a single heat source or b) one building in which there are more than ten individual customers connected to a single heat source. Heat networks are therefore well-suited to areas where there is a high heat demand density. Of those operating in the UK, a large majority are not supplied by a CHP system – something which is more commonly found among larger networks. Heat networks can distribute heat produced from various sources: industrial processes, energy-from-waste facilities, geothermal sources, heat pumps, fuel cells, solar arrays and combinations of these. However, although DECC's database only records information on fuel type from 40% of the networks included (and so these figures should only be regarded as approximate indicators), within this 40% the overwhelming majority (90%) use only one type of fuel – typically gas (85%). Other fuel options include oil, coal, LPG, biomass and waste, with oil as the second most common fuel type. A comparison between district heating based on waste incineration with biomass or natural gas found biomass environmentally favourable with regard to avoided electricity generation (if the avoided fuel has a high carbon content) and waste management. Waste incineration is frequently the preferable choice when the alternative is landfill disposal but never when it is recycling (Eriksson et al., 2007).

Low carbon heating systems more generally suffer from a lack of mass market demand, poorly developed national and international supply chains and a shortage of the skills required for installation, maintenance and repairs. The economics of heat networks are closely associated with the heat demand density of the areas they serve, with higher demand density requiring less capital expenditure – the main driver of cost being the initial paying of distribution pipes – and so providing greater payback certainty (Hawkes et al., 2011). However, under some circumstances this may not be the case: for example, greater costs may be incurred owing to disruption in congested city centres, whilst costs could be lower in any rural areas with a high population density. Some combinations of fuel sources and building types can be more competitive. For example:

- The use of waste heat from existing power plants sited close to areas with sufficient heat demand
- Where district heating replaces electricity as a heating fuel
- The supply of heat to commercial premises and residential flats where heat density is very high

An alternative to supplying hydrogen direct to consumers' homes is its use in district heating networks, or indeed single-block heating systems, either blended with natural gas or combusted as pure hydrogen, which can then be used in a variety of boilers and engines. As heat networks themselves are neutral with regards to heat source, this also leaves open the possibility of retrofitting hydrogen technologies to existing heat distribution networks if and when such technology becomes sufficiently commercially developed, and contingent on the availability of sufficient volumes of competitively-priced low carbon hydrogen.

In the long term hydrogen fuel cells may be able to compete in certain niches where, for example, local air quality regulations cannot be met by alternative low carbon fuels such as biomass, or in certain new build or properties off the gas grid, the latter of which sees the replacement of around 150,000 heating systems each year. The commercial and industrial sectors may be less accepting than residential consumers due to the assessment of competing heat technologies on the basis of economic rationality, technical performance and the availability of replacements parts and maintenance. Public sector organisations may be more willing to take on flagship projects, however: Transport for London has recently installed a 200kWe fuel cell that provides power, heating and cooling for its offices and which is estimated to reduce emissions by 40% and generate savings of £90,000 per year (Logan Energy, n.d.). Currently the only example of a hydrogen fuel cell unit integrated into a heat network is operated by Woking Borough Council (Dodds and Hawkes, 2014).

13.14 Conclusions

- Literature more often discusses the establishment and configuring of infrastructure systems over time rather than transitions *from one system to another*, on which less is available.
- Historical examples rooted in transitions theory do not always address *infrastructure* and so often of limited relevance here.
- Water networks have in the past grown more slowly in existing cities because of the cost of breaking up streets.
- Public ownership and local authority involvement appear to be important for success with district heating networks.
- Co-ordinated, concerted local action backed by central government greatly increases the chances of success.
- Projects tend to be driven by motivated and informed champions.
- Even where novel end-use technologies drive change, this starts off imperfectly and expensively before being scaled up to drive the transition forward.
- Gaining access to a large numbers of homes presents a challenges.
- District heating works best if there is guaranteed demand, ideally starting with a blank canvas.
- Networks in general require sufficient demand and are often developed more slowly to poorer areas where demand (or anticipated demand) is lower.
- Technical standards can play an important role in network transitions.
- Carbon capture and storage could be critical to low carbon gas options (as well as for decarbonised electricity and heat networks).
- There has been relatively little research on managing peak heat demand in the context of low carbon heating provision.

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