IEA HPP Annex 42: Heat Pumps in Smart Grids

Task 2: Review of Modelling Studies

1st July 2014

Report compiled by:

Delta Energy & Environment; University of Ulster

This report is Task 2 of 4, and reviews the modelling studies in the UK. The full list of 4 reports is listed below:

Task 1: This consists of a UK market overview and an analysis of the smart-ready capabilities of heat pumps on the UK market – and expected to come to the UK market

Task 2: (this report) This report summarises the major UK modelling studies which have investigated issues linked to the use of heat pumps for load shifting. This report assesses the extent to which these modelling studies have sufficiently addressed DECC's core questions in relation to this project – and identifies areas of further work which would support DECC's core questions.

Task 3: This report summarises the major UK demonstration projects involving heat pumps in load shifting. It assesses the extent to which DECC's core questions are being tested and identifies areas of further work.

Task 4: The aim of this report is to summarise the assessments of modelling and demonstration projects in Tasks 2 and 3, and make recommendations on where the evidence gaps are which warrant further work in order to fully answer DECC's core questions.

Table of Contents

Table of tables / figures

DELTA Energy & Environment

1. Executive Summary

We have assessed four major UK modelling studies which consider the use of heat pumps within demand side response (DSR) applications, looking at the outputs of the study in comparison to the insight required to answer DECC's core questions in the context of this research under IEA Heat Pump Programme Annex 42. The sophisticated modelling approaches in the studies assessed can give effective broad brush indications of the overall impact of heat pumps on peak demand at a large geographical scale. But to more effectively answer DECC's core questions, **modelling of the heat pump process should be informed by more granular data.** The studies need to be based on a more consistent data set of real heat pump performance and its influencing factors, and need to incorporate a more dynamic heat pump module into the modelling in order to provide sufficient insight to DECC. Specifically, it is difficult to draw conclusions about the use of heat pumps to manage local distribution grid challenges without using more granular data.

The modelling studies have several common elements which mean their value for specifically tackling DECC's core questions related to heat pumps is limited

- **None of the studies have a specific aim relating to heat pumps for use in peak shifting** – but all are focusing on identifying network challenges or investigating the benefits of demand side response (DSR) at a wider system level.
- All studies investigated do include heat pumps, but because it is not the core study focus, in general, **the modelling of heat pump dynamics is relatively simplistic** (the modelling is considered at a network level and assumes heat will be supplied at the required level. None of the studies address the characteristics and dynamics of heat pump systems in sufficient detail to provide answers to DECC's current questions).
- **There is a need to develop and build in a further heat pump module to existing models** (e.g. Plexos or as a complementary element to such modules that incorporates start behaviour, the impacts of end-user randomisation, different storage needs and accounts for differing heating needs) – or develop new models – in order to better answer DECC's questions.

The main challenge that all these studies have faced is the lack of consistent and granular heat pump data (e.g. from field trials) to adequately represent the dynamics of heat pump performance and the factors which influence it

There will always be uncertainties in modelling relating to characterising key variables such as heat pump type, type of heat emitters, availability of storage, and HP efficiencies – these variables have a significant impact on how effectively heat pumps can be used for peak shifting. The studies we have looked at tend to have a top down approach informed by bottom up information – this leads to too few variables being considered e.g. no differentiation between air source and ground source, retrofit and new build, underfloor heating and radiator heating. The studies have, for example, relied on heating pattern data from studies such as the micro-CHP field trial coupled with predictions on heat pump market growth to inform impact on the GB wide electricity consumption and electricity markets. To build more robust assumptions about heat pumps (and specifically their potential for peak shifting), there is a need for more consistent heat pump data to be used as input to the modelling.

We present in Table 2 a summary of the type of information a modelling study should ideally provide which would provide insight to DECC's key questions. Comparing this with the modelling studies investigated, several main "gaps" are identified.

Identifying the main gaps in the modelling studies

In Task 4 of this set of report we have carried out a gap analysis to identify where further work is required through modelling or demonstration projects to better answer DECC's core questions. Below we summarize the main evidence gaps we have identified based only on the modelling studies. Demonstration projects assessed in Task 3 may tackle some of these gaps.

MODELLING GAP 1: Investigating mechanisms of achieving peak shifting with heat pumps

The modelling has only partially considered different mechanisms for peak shifting with heat pumps:

- Where the studies have investigated changing the operating times of heat pumps for peak shifting, this has been with on-off cycling for a set period, using a fixed volume of storage.
- None of the studies have investigated the use of modulation, or the use of a second energy source to extend the amount of flexibility from the heat pumps.
- Where the studies have assessed the response to different types of tariffs, this has been a purely economic model finding the least cost or most beneficial scenario. This modelling has not incorporated technology or end-user response to different tariff types.

MODELLING GAP 2: Simulating use of storage and heat pump / storage interaction

This has been done relatively simplistically in modelling:

- The interaction of the heat pump with storage is modelled relatively simplistically, not capturing the dynamic operation – in all studies, further investigation would be required to draw realistic conclusions about how much flexibility storage could provide.
- Assumptions are generally made that physical space for storage is available in modelled buildings for storage – further investigation is required to ascertain how well this can be translated across the building stock where large portions of the stock will *not* have available space.
- None of the models test scenarios with different volumes of storage.
- The required parameters to better model storage and quantify peak shifting capability, is understanding store status and available capacity i.e. compressor run time (electricity consumption) based on temperature conditions derived from heat source temperature and heat supply temperature. From the DNO perspective, has sufficient heat been stored to avoid compressor starting during peak times? All of this must be based on meeting thermal comfort needs.

MODELLING GAP 3: Simulating heat pump operating patterns and influence on electricity consumption

This has been done relatively simplistically:

- In most models, the on-cycle and off-cycle do not take fully into account the different operating dynamics of different type of heat pumps in different types of building (new build and retrofit, with underfloor heating or radiators). These factors mainly impact "ramp up" speeds, and on the operating pattern during the day. The ramp up speed affects the rate of response of the system, which is critical for the Transmission System Operator (TSO), Distribution Network Operator (DNO) and the end user.
- There is an assumption of instantaneous electricity consumption by the heat pump in response to any signal - where in reality it is not always instantaneous. Variable speed compressors and the temperature of the heat source and the start temperature of the building (interior temperature and heat distribution medium temperature) add a response time. Electricity response time is relatively short and therefore DSO/TSO aspirations in terms of DSM/DSR are readily achievable provided it is recognised that this process is not instantaneous.

MODELLING GAP 4: Capturing the dynamic characteristics of heat pump system operation

The modelling studies are not dynamic in relation to the heat pump modelling:

- None of the studies are at sufficient resolution or scale to capture, for example, the "ripple effect" when controlling multiple heat pumps
- Some have a relatively high temporal resolution (e.g. 10 minutes) which could provide an indication of the dynamic nature of, for example, modulation – but ideally resolution should be higher than this.
- Only one model explicitly considers the impact of external dynamic variables such as outside temperatures on heat pump operating patterns and performance. There is an opportunity for more detailed modelling, potentially including local weather forecasting.

MODELLING GAP 5: Assumptions about how thermal comfort is being met

Modelling assumes thermal comfort is satisfied in all cases, but does not consider the factors affecting this:

- *Impact of type of HP and type of building:* In reality there is a difference in how well thermal comfort can be achieved between different types of heat pump installed in different types of buildings. For example, ASHPs running as a higher temperature retrofit with traditional radiators have the possibility of meeting electricity management needs but less so thermal comfort needs. Current 30 minute market segments may provide insufficient run times to attain thermal comfort. However a GSHP operating with underfloor heating tends to operate for longer periods of time and therefore has the greater potential to operate from a warm/hot start and therefore meet the needs of all parties. Further, the potential changes in operating regime coupled with thermal mass associated with underfloor systems may make the modelling approach of near instantaneous on-off heat pumps acceptable.

- *Impact of storage characteristics:* The status and response time of storage is critical in determining peak shifting potential whilst maintaining thermal comfort. Storage systems are not considered in modelling studies in any great detail. ‘Status’ refers to temperature i.e. their ability to store heat (based on previous use and losses). As sizing guidance has yet to be developed on the size of storage with heat pumps for DSM (other than for example 3 hours capacity), it is understandable that this has not been considered in detail, because this would be a significant study in its own right.
- *Impact of end-user behaviour*: None of the models explicitly address the impact of “random human behaviour” on the heat pump operating patterns e.g. the impact of manual override of the system. This may be indirectly included in 2 of the studies which model based on ‘no impact on end-user comfort’.

2. High Level Summary of modelling studies

This summary table will highlight the key gaps in the current modelling studies from the UK

TABLE 1: SUMMARY TABLE OF UK MODELLING STUDIES

	Element Energy/Redpoint (2012)	Imperial College/NERA (2012)	Smart Grids Forum: Workstream 3	DECC: Follow up to household electricity survey
Do the study aims try to tackle DECC's core questions?				
Flexibility	✓	✓	✓	✓
Customer response	✓	✓	✗	✓
Building Response	✓	✓	✗	✓
Heat Pump Response	No specific aims ✗	only economic ✓	No specific aims ✗	✓
Assumptions - robustness				
Power supply	✓	economic perspective not technical ✓	✓	✓
HP integration with storage	✓	✓	✓	✓
HP operation & performance	✓	✓	✓	✓
Building dynamics	✓	✓	✗	(based on small sample) ✓
Occupancy patterns	✓	✓	✗	(based on small sample) ✓
Would additional simulations add critical insight to answer DECC's questions?				
Under different scenarios?	only with development of HP part ✗	only with development of HP part ✗	only with development of HP part ✗	only with development of HP part ✗
With higher sampling rate?	✗	✗	✗	✗
With further development of heat pump part of model?	detailed HP module should be added ✓	more detailed characterisation of HPs ✓	detailed HP module should be added ✓	develop with wider sample of real HP data ✓
Key gaps	Needs HP module built into model which considers the impact of different types of HP (e.g. ASHP/GSHP) performance, end use characteristics, storage volume and random end-user behaviour.	HP part of model needs to be developed to consider differences between operation in retrofit or new build, the interaction of the HP with storage, and random end-use behaviour.	Advancement of the low voltage (LV) model to incorporate HPs (& EVs) in a less simplistic way – specifically needs to consider building dynamics and variations in end-user characteristics	Is based on a small sample of real data – wider sample would be beneficial. Should consider HP dynamics (e.g. differentiation between HP types & retrofit / new build).

KEY: WHAT DOES THE RATING MEAN?

Rating	Description	Rating	Description
	Issue addressed, and in a robust way		Plan to address issue fully based on current literature – but modelling still on-going
	Issue addressed, but only on limited scale / not robustly		Plan to address issue partially – but modelling still on-going so it may yet be covered in more robustly
	Not addressed at all		No plan to address this issue based on current literature – but modelling still on-going so there may yet be development

3. Detailed review of modelling studies

The following projects have been identified in the UK.

- **Element Energy/Redpoint** (2012) Electricity System Analysis – future system benefits from selected DSR scenarios Report Prepared for the Committee on Climate Change, October 2013
- **Imperial College London/NERA Economic Consulting** (2012) Understanding the Balancing Challenge
- **Element Energy, GL Noble Denton, Frontier Economics, Chiltern Power, EA Technology Ltd** (2012) Paper 82350, Smart Grids Forum: Workstream 3 - Developing Networks for Low Carbon: Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks,
- **Element Energy** (2014), Further Analysis of Data from the Household Electricity Usage Study: Correlation of Consumption with Low Carbon Technologies – Department of Energy & Climate Change

3.1. Information collected in an 'ideal' modelling study

Here we will describe within the template the type and level of information which would be necessary from an 'ideal' modelling study to provide real and meaningful conclusions for DECC. This 'ideal' study will then be used as a basis for identifying the 'gaps' in the assessed modelling studies.

TABLE 2: 'IDEAL' MODELLING STUDY

Overall project info	
Project aim	There is a range of modelling study aims which would be relevant to DECC. Key topics include: 1. Simulating technical possibilities & potential of demand side management e.g. - Testing ways to managing congestion on distribution grid - Quantifying the impact of distributed generation on grid voltage - Testing the use of different distributed generation technologies in demand side management 2. Simulating socio-economic aspects of capturing demand side flexibility: - testing business models and market mechanisms – quantifying value streams - testing the impact of human behaviour / customer response Ultimately, the aim of DECC's current research is to uncover specific conclusions about the use of heat pumps in such applications. Therefore, the ideal modelling study should include simulations of heat pumps as (at least) one form of distributed generation / flexible demand side resource. Model runs should aim to support the ultimate goal of quantifying how much flexibility can come from HPs.
What is it specifically testing in relation to heat pumps	
Methods being used/tested for getting flexibility	Where the modelling study does consider heat pumps specifically, DECC ultimately needs a study which tests how much flexibility can be captured through different mechanisms e.g. - Shut-down of the heat pump for a time period - Modulation down to e.g. 30% rather than shut-down - Use of thermal storage of different capacities / types - Use of hybrid or bivalent systems instead of or in addition to thermal storage - Use of building thermal mass as a type of storage
Robustness of model	
Is the model dynamic?	The modelling study should consider the system elements in a dynamic way. In order to draw conclusions from the results, assumptions should be clear on the 'response time' for the

	heat pump, the thermal store and the building. For example, does the model consider whether the heat pump starts instantaneously or the extent to which there is a "ramp up" delay? Does the model consider the dynamic nature of operation throughout the day in response to the storage capacity, building response, end-user behaviour, and outside environment – or does it assume a flat operation? Modelling of the heat pump should take into account both how it can satisfy electricity network demands (electricity usage) and how it can satisfy end-user comfort (responding to existing heat in the building, use of buffer or storage).
Assumptions about power supply	The model needs to consider e.g. cable size and DNO safety margins for Low Voltage (LV) circuits at nominal values of 400V or 230V
Assumptions about HP-storage interaction	Storage is a critical element in defining flexibility from heat pumps. Assumptions in the model should be clear on e.g. what volume of storage tank is included? Is the storage at the building interface? Does the HP always heat the store first? Potentially a more complex control system is needed to ensure satisfaction of all participating parties in DSR schemes.
Assumptions about HP	To draw conclusions from the modelling studies on the flexibility achievable with heat pumps, assumptions need to be clear regarding: - Type of heat pump being simulated e.g. GSHP (more stable), ASHP (more variable) - Performance of HP – and how variable is it? (e.g. is a flat SPF anticipated throughout the simulation period?) - Design of the HP system within the building? e.g. has the HP been designed to meet 100% of demand? What is the design point? Is there a role for electric boost heaters/gas hybrids in legionella control and/or low temperature top-up?
Assumptions about building	Building characteristics have a significant impact on the level of flexibility provided by heat pumps. Assumptions should be clear regarding e.g. the building type(s) being simulated, the heat loss and the building thermal mass.
Assumptions about occupants	End-user behaviour (i.e. how and when they use heat) influences the HP operating patterns - and therefore influences HP performance and flexibility achieved. Assumptions should be clear on how the model simulates specific occupancy patterns, including associated heat demand profiles, domestic hot water profiles etc.

Resolution / level of depth & detail of modelling	
Sample rate / time resolution	In order to capture the subtleties of real heat pump operation, enough variables should be considered to get results reflecting e.g. - Modulation (does it just capture 0% and 100% or points in between? - A single extreme 4 hour shut-down versus a series of short <30 min shut-downs - Ripple effect when controlling operating times of multiple heat pumps? - Variable response times of heat pumps in different scenarios - It is recognised that some of this subtly may be lost in aggregating individual units into overall models but this effect needs to be clearly understood.
Error margins	Error margins and confidence levels regarding all outputs e.g. performance, response times, grid voltage impact etc should be clearly identified
Number of model runs / scenarios tested	The key for DECC is that model runs and scenarios which have been tested are addressing issues relevant to the current research. The greater the number of scenarios tested which are relevant, will create more meaningful results. It is also key to understand whether there is scope for using the model for further scenario testing.

3.2. Element Energy/Redpoint (2012) Electricity System Analysis – future system benefits from selected DSR scenarios Report Prepared for the Committee on Climate Change, October 2013

TABLE 3: ELEMENT ENERGY / REDPOINT

Overall project info	
Wider context	This project provides modelling on the potential benefits of Demand Side Response (DSR) from domestic customers and Small and Medium Enterprises (SME) over the medium term to 2030. This project draws on several other sources: It makes use of DECC's Updated Energy and Emissions Projections (2012) Central scenario; the demand profile is based on Elexon profile coefficients; the load profiles are based on thermal demand measurements in a range of dwelling types (Carbon Trust Micro-CHP field trials); and the rate of COP improvement over time is based on the Design of the Renewable Heat Incentive (NERA for DECC, 2010).
Participants	Redpoint, Barunga, Element Energy
Funding	Department of Energy & Climate Change (UK)
Timing	Completed
Project aim	**The main aim is modelling the potential benefits of Demand Side Response (DSR) from domestic customers and Small and Medium Enterprises (SME) over the medium term to 2030.** The technical potential of DSR for the SME sector is explored at a high level in order to evaluate benefits from both a distribution network and wider system perspective against a number of background scenarios and different DSR tariffs. This is enabled through electric vehicles and heat pumps. The study notes the benefits of DSR in terms of avoided distribution network investment, avoided generation investment and avoided operational generation costs based on DSR for domestic and SME demand. There are no *specific* aims relating to the use of heat pumps for peak shifting.
What is it specifically testing in relation to heat pumps	
Methods being used/tested for getting flexibility	Heat pumps are one of 4 scenarios which operate within the five following tariff scenarios: - BAU (Business As Usual) - SToU (Static Time of Use) - LC1 (Load Control 1, applied on 30 peak days per year)

	- LC2 (Load Control 2, applied on all days in year) - CPP (Critical Peak Pricing). This is a high level model based on overall assessments of data and provides market uptake rates for heat pumps. However, the use of heat pumps for peak shifting, or the flexibility potential provided by heat pumps, is not specifically investigated.
Robustness of model	
Is it dynamic?	**Considers the dynamic nature of the HP start characteristics but not the overall dynamic operation:** This is a market study and assumes levels of penetration based on an overall GB PLEXOS model. This means the model does incorporate some of the dynamic nature of heat pump operation relating to the start characteristics. Plexos can incorporate the characteristics of the "ramp up" (as well as electricity costs) dependant on the type of heat pump (ASHP or GSHP) and its mode of operation (new build/full renovation or retrofit): - New build/full renovation = GSHP or ASHP installed with underfloor heating and semi-continuous slow heating – which may mean near instantaneous start of heat delivery if operated in the ideal way. - Retrofit = Typically ASHP installed with existing radiators – which means "cold start" characteristics of about 30 minutes to obtain useful heat. However, Plexos cannot currently comprehensively account for further dynamics of operation in response to the building, occupants or outside environment.
Assumptions about power supply	**Considered:** DNO reinforcement costs (or avoidance) where assessed by an Imperial College London model on the basis of the Distribution Price Control Review 5 (DPCR5) cost appendix (published by OFGEM and used as the basis of distribution network operator network investment planning).
Assumptions about HP-storage interaction	**Not considered in sufficient detail:** Three hour storage capacity is assumed in the model but no information is given about this or its characteristics.
Assumptions about HP	**Partly considered – but excludes dynamics of operation**: The overall model is based on bottom-up modelling of heat pump uptake in the domestic stock based on consumer willingness-to-pay analysis (calibrated to DECC heat pump uptake projections). Modelling of the domestic heat pump demand profile is based on analysis of heating demand data recorded through the Carbon Trust's micro-CHP field trials, which is then deployed through a GB housing stock model. Heat pump COP improvement over time are assumed to be from 2.5 to 4 for ASHP and from 3.3 to 4.8 for GSHP (based

	on Design of the Renewable Heat Incentive (NERA for DECC, 2010)). Dynamics of heat pump operation are not mentioned.
Assumptions about building	**Considered:** The GB housing stock model has 10 distinct house types. The stock model includes regionally specific variations based on English, Scottish and Welsh Housing Condition Surveys. Domestic and SME electricity demand profiles for the buildings are derived using Elexon profile coefficients.
Assumptions about occupants	**Partly considered – but does not consider human behavioural patterns.** The Standard Assessment Procedure (SAP) is used to define building energy use. The Standard Assessment Procedure (SAP) is the Government's standard method of rating the energy efficiency of a dwelling. The Building Research Establishment (BRE) has developed the current and previous models on behalf of Government. Human behaviour is negated through a 100% response assumption.
Resolution	
Sample rate	**Based on block assumptions across building stock sectors:** This is an overall housing stock model with block assumptions made i.e. the individual aspects of overall energy usage are amalgamated, so the model outcomes cannot provide sufficient resolution to draw conclusions about variance within each housing stock block.
Error margins	Not given
Number of model runs	Not given
Results available	
Flexibility	The PLEXOS model was used to generate GB wide model incorporating generating plant characteristics, interconnection responses and wind loadings. No dynamics are included for DSR heat pump response. Flexibility is achieved in the model - peak demand is reduced by shifting flexible load away from peak periods, with higher demand scenarios show the greatest potential for peak demand reductions. The most significant results are a £500M reduction in costs associated with reducing investment in OCGT peaking plant and DNO reinforcement, as well as reduced operational generation costs by 2030 when Heat Pumps are deployed at the predicted level.
Customer response	Results are provided on market growth and penetration of heat pumps and electric vehicles as driven by financial characteristics. Response to different tariffs is explored and

	Critical Peak Pricing tariffs were found to give the largest peak demand reductions, while Load Control tariffs (where 3rd party could control the operating times daily throughout the year) gave the flattest demand profile through the year. But there are no results considering non-technical/economic influencing factors such as customer behaviour, changing occupancy patterns, or the impact of manual override.
Building response	The stock model may relate SAP style data to response i.e. low SAP indicating high energy needs. There are no specific results presented regarding the response of different types of building.
Heat Pump Response	None indicated which provide insight into the dynamic operation of heat pumps in different settings.
Gap analysis	
How big a range of scenarios were simulated?	This is a high level study indicating market possibilities, but several heat pump scenarios were not investigated.
Would the simulation of different scenarios add value to DECC?	To better answer DECC's core questions, there is a need for a specific heat pump simulation using a new heat pump module for the model.
Robustness of assumptions	The assumptions were sufficient to indicate at a high level heat pump market size and network possibilities – but were not robust enough to provide any conclusions regarding available heat pump flexibility (i.e. do not account for dynamic operation, and the incorporation of storage).
Would a higher sampling rate provide critical insight?	No – unless a new heat pump module is developed for the model.
Recommendations	**A PLEXOS style heat pump module requires development** taking into account equipment performance, end use characteristics, storage volume and random end-use behaviour. It should be based on a standardisation of heat pump sizing and storage. Some of the above challenges are being now addressed in the University of Ulster led Interreg IVA project SPIRE.

3.3. Imperial College London/NERA Economic Consulting (2012) Understanding the Balancing Challenge

TABLE 4: IMPERIAL COLLEGE LONDON / NERA ECONOMIC CONSULTING

Overall project info	
Wider context	This project is driven overall by the need to address the challenges faced by the electricity system in meeting the Government's decarbonisation objectives – in particular the increasing system integration costs (defined in this report as "the balancing challenge". This study assesses how alternative balancing technologies can help to mitigate this challenge.
Participants	Imperial College London & NERA Economic Consulting
Funding	EPSRC, UKERC, Supergen HiDEF, Supergen Hubnet re acknowledged
Timing	This stage of modelling is complete but the report highlights future work including valuing potential investments in alternative balancing technologies, market-based modelling allowing for competitive behaviour between companies and European countries, a more detailed representation of neighbouring European markets, and analysing the investment profile of distribution networks and how it is influenced by heat pumps, electric vehicles, DSR and embedded generation. Some of this follow up work (particularly the latter part) may be relevant to DECC's core questions within this Annex 42 project.
Project aim	There are three main aims highlighted: • Assessing the scale of the system balancing challenge from 2020-2050 • Assessing the merits of and interaction between alternative balancing technologies in terms of minimising the costs of balancing • Identifying the barriers to efficient deployment Heat pumps are a part of the project but there are no specific aims relating to the use of heat pumps for peak shifting.
What is it specifically testing in relation to heat pumps	
Methods being used/tested for getting flexibility	Overall the models are presented from a least cost basis rather than testing any technical potential for capturing heat pump flexibility. Consideration is given to changing operating patterns of heat pumps, with the main constraint being that space heating needs are never compromised.
Robustness of model	
Is it dynamic?	**The model is dynamic in its consideration of building response – but not so regarding heat pump or end-customer response**. Patterns in thermal loads are utilised

	through detailed building thermal modelling so dynamic building response is addressed well.
Assumptions about power supply	**Considered from an economic perspective:** The economics of cable sizing and re-cabling etc are considered
Assumptions about HP-storage interaction	**Not considered in sufficient detail:** The model assumes each building has storage – this assumes that all buildings have available space for storage, which may be questionable. No details are included on the characteristic of the storage or how it interacts with the heat pump.
Assumptions about HP	**Considered – but no differentiation made based on type of heat distribution.** Consideration is given to the operating patterns of the heat pump, and the influence of decreasing ambient temperature is accounted for. The heat pump is assumed to meet thermal comfort demands (regardless of type). An assumption is suggested in the report that HP operation should mimic current boiler (or micro-CHP) use. This assumption is only valid for retrofit heat pumps using the existing high temperature heat distribution infrastructure of the building. It does not consider the operating patterns of GSHP or ASHP operating with underfloor heating, which may have longer run times and less dynamic characteristics (e.g. the start time influences are distinctly different dependent on the heat distribution system. With radiators, a delay should be anticipated for full ramp up of the heat pump, but in new build the more constant nature of the heating means the ramp up is fairly instant).
Assumptions about building	**Considered**: Commercial and domestic buildings with knowledge of construction type, insulation and control strategies.
Assumptions about occupants	**Considered but without taking into account occupant behaviour:** The model has access to occupancy patterns (and inside and outside temperatures). But does not model any aspect of human random behaviour.
Resolution / level of depth	
Sample rate	Modelling reports hourly. With each building assumed to have storage over and above thermal mass (which is not the case with combi boilers), the value of hourly resolution data is interesting as it must be assumed that distributed energy storage will be the responsibility of the HP installer.
Error margins	Wind forecasting error 10%
Number of model runs	Not given

Results available	
Flexibility	The modelling approach is such that flexibility can be provided at the required level, but is based on economic feasibility across the whole energy system and does not draw conclusions about the technical or economic feasibility of providing flexibility specifically from heat pumps. A storage model and Heat Pump model are available at a UK building stock model level, but may be required at an individual building level in order to provide results regarding available heat pump flexibility for peak shifting.
Customer response	The modelling assumes heat pumps can be used for DSR within the limits where thermal comfort is not impacted - therefore there is no specific customer response recorded.
Building response	Thermal response models are used against scenarios ranging from high efficiency retrofits to lesser retrofits. Therefore the impacts reported in the conclusions are referring to UK DSR potential, losing any possible conclusions regarding individual behavioural aspects.
Technology Response	Results are provided for Heat Pumps and EVs on local networks based on a range of renewable energy penetration scenarios of 43GW to 108GW by 2050 leading to 40TWh to 120TWh of electrified domestic heat.
Gap analysis	
How big a range of scenarios were simulated?	DECC's Carbon Plan scenarios are utilised ranging from high renewables, high energy efficiency and high demand electrification to medium energy efficiency, low demand electrification. Thus there are studies ranging from full electrification of heating, high levels of transport electrification and the highest levels of insulation and behavioural change, to lower implementation levels of around 50% heat pumps with modest building efficiency improvements.
Would the simulation of different scenarios add value to DECC?	Scenarios are good, but to better answer DECC's core questions they would benefit from the addition of heat pump and storage characteristics into the scenarios.
Robustness of assumptions	Heat Pump/Storage response to thermal comfort requires further investigation. The assumption of storage always being available is also questionable.
Would a higher sampling rate provide critical insight?	No
Recommendations	**Heat Pump characteristics** (whether in retrofit or new build, and different modes of operation), and the **interaction with storage** (size, available space etc) needs further investigation.

	Mode of operation should be considered e.g. cold, warm or hot starts leading to different inertial responses affecting householder satisfaction and energy storage/ building heating. There are no details on how **the impact of human random behaviour** is modelled (the assumption that comfort is always satisfied may address this issue to some extent).

3.4. Smart Grids Forum: Workstream 3 - Developing Networks for Low Carbon: Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks, Element Energy, GL Noble Denton, Frontier Economics, Chiltern Power (2012) Paper 82350, EA Technology Ltd

TABLE 5: SMART GRIDS FORUM: WORKSTREAM 3

<table>
<tr><th colspan="2">Overall project info</th></tr>
<tr><td>Wider context</td><td>The main issue discussed within the DECC/Ofgem Smart Grid Forum is how electricity network companies will address significant new challenges as they play their role in the decarbonisation of electricity supply.</td></tr>
<tr><td>Participants</td><td>Element Energy, GL Noble Denton, Frontier Economics, Chiltern Power</td></tr>
<tr><td>Funding</td><td>OFGEM</td></tr>
<tr><td>Timing</td><td>Ongoing model development (version 1.21 was evaluated in this document)</td></tr>
<tr><td>Project aim</td><td>There are several key aims:
Identifying future challenges for electricity networks and system balancing, including current and potential barriers to efficient deployment of smart grids
Guiding the actions being taking with DECC to address future challenges, remove barriers and aid efficient deployment
Identifying actions that could be taken to facilitate the deployment of smart grids
Facilitating the exchange of information and knowledge between key parties, including those outside the energy sector
Helping all stakeholders better understand future developments in the industry that they need to be preparing for
Tracking smart grid developments and their drivers
Tracking smart grid initiatives in Europe and elsewhere.
Heat pumps are included within the modelling but there are no specific aims relating to the use of heat pumps for peak shifting.</td></tr>
<tr><th colspan="2">What is it specifically testing in relation to heat pumps</th></tr>
<tr><td>Methods being used/tested for getting flexibility</td><td>There is no modelling of heat pump on-off cycling or modulation in response to control / influence. Inclusion of heat pumps is limited to the use of a lumped model which indicates the level of power consumed in any ½ hourly period.</td></tr>
</table>

Robustness of model	
Is it dynamic?	Yes, to some extent: Average profile in 48 half-hourly segments developed from “limited” field trial data which incorporates the different types of heat pump (ASHP and GSHP, new build and retrofit) and thus is a first estimation. Storage elements are added as a % of installed stock as HP deployments grow. A characteristic graph is presented for example that illustrates peak time (4-6pm) shut down and 00:00 to 4am operation. Non-zero power is shown during off states so this may imply underfloor heating systems only on a night set back mode.
Assumptions about power supply	The variance of LV, HV cabling etc is the major objective of the study with thermal rating being a primary concern
Assumptions about HP-storage interaction	**Not considered in sufficient detail:** The inclusion of 100L to 400L of storage were noted, but the details provided would be inadequate for drawing conclusions regarding DSR potential.
Assumptions about HP	**Not considered in sufficient detail:** Heat pump winter profiles have been developed (commercial and domestic) and these form a generic profile which is assumed to be multiplied by the number of future installations. A percentage year-on-year heat pump market growth is predicted at three levels, from the current rates to increased rate of penetration. The model of the heat pump is based on an average of current installations. No differences in operation between types of heat pumps or different sectors (e.g. new build, retrofit) are noted.
Assumptions about building	**Not considered**
Assumptions about occupants	**Not considered**
Resolution / level of depth	
Sample rate	Half-hourly modelling (electricity market periods)
Error margins	Not given
Number of model runs	Not given
Results available	
Flexibility	Not given – project still underway, but based on existing work, results are unlikely to allow conclusions regarding heat pump flexibility for peak shifting.
Customer response	Not given – project still underway, but customer dynamics not discussed in the literature so no clear results expected.

Building response	Not given – project still underway, but building dynamics not discussed in the literature so no clear results expected.
Technology Response	The effect of thermal storage is accounted for in the model by moving demand from peak to non-peak times.
Gap analysis	
How big a range of scenarios were simulated?	Scenarios ranged from a BAU to “Smart Incremental Investment Strategy”, the latter representing the lowest investment choice
Would the simulation of different scenarios add value to DECC?	Further simulations would only be useful if a more detailed heat pump module was incorporated.
Robustness of assumptions	The heat pump model appears simplistic at this stage, providing only broad brush indications, but will not reveal any subtlety on the low voltage (LV) network for example.
Would a higher sampling rate provide critical insight?	No
Recommendations	Advancements in LV model that incorporates HP, PV, EVs and thermal storage interaction would enable DECC to better answer their core questions.

3.5. Further Analysis of Data from the Household Electricity Usage Study: Correlation of Consumption with Low Carbon Technologies – Element Energy

TABLE 6: FURTHER ANALYSIS OF DATA FROM THE HOUSEHOLD ELECTRICITY USAGE STUDY

Overall project info	
Wider context	Built on the Department of Energy and Climate Change (DECC), the Department for the Environment Food and Rural Affairs (Defra) and the Energy Saving Trust's Household Electricity Usage Study (HEUS)
Participants	Element Energy
Funding	DECC
Timing	Published July 2014 https://www.gov.uk/government/collections/household-electricity-survey
Project aim	The project investigated how the electricity consumption profiles for typical English households, as recorded by the HEUS, will be impacted by the uptake of LCTs including electric vehicles (EVs) and heat pumps, as well as domestic solar photovoltaic (PV) and micro-wind generation systems.
What is it specifically testing in relation to heat pumps	
Methods being used/tested for getting flexibility	The study uses typical profiles of electricity demand from heat pumps. Three installed and monitored heat pumps were used and extrapolated against other households in the study. The approach assumes just over 2kW fixed cycle time approach with an on-off approach. The on and off characteristics are not discernable from the presented graphs.
Robustness of model	
Is it dynamic?	**Some but not all elements are dynamic:** Electrical consumption is not dynamic but linear (100% on/off). The thermal storage model is based on the availability of 180 litres of storage – some consideration of dynamics here as a response time has been noted. On-off characteristics are considered to occur within a 10 minute period.
Assumptions about power supply	**Considered:** Network demand increases noted
Assumptions about HP-storage interaction	**Interaction is considered:** Storage and heat pump are integral as storage is used to offset heat pump operation time.
Assumptions about HP	**Considered – though based on small sample of real systems and not differentiating between types of system:** It is assumed that those heat pumps used in the study have been installed according to the appropriate standards. The

	main limitations of the study are that assumptions for heat pumps are based on just three monitored systems, and there are no distinctions made between the operation of GSHP or ASHP, or the operation of HPs in new build or retrofit.
Assumptions about building	**Considered - but based on small sample**
Assumptions about occupants	**Considered – but based on small sample:** The heat pump is assumed to meet all heating needs and the model is based on the three real monitored heat pumps, which therefore incorporate some element of human behaviour (though details of this influence are not discussed).
Resolution / level of depth	
Sample rate	As per study requirements scan rate was insufficient to note accurately heat pump subtleties. Sampling was at 10 minute resolution.
Error margins	None noted
Number of model runs	Two groups of runs: Modelling based on actual data with simulations of HP *with* and *without* 180L tank for DSR
Results available	
Flexibility	Outcomes from three homes extrapolated across wider household energy use data set
Customer response	Not noted
Building response	Not noted
Technology Response	DSR noted
Gap analysis	
How big a range of scenarios were simulated?	Scenarios based on low, central and high LCT uptakes
Would the simulation of different scenarios add value to DECC?	Further scenarios not valuable without integration of wider heat pump model.
Robustness of assumptions	The assumptions are based on limited real data (sample of 3)
Would a higher sampling rate provide critical insight?	Wider HP data studies will inform the study
Recommendations	Wider heat pump models required, based on larger real sample, and which consider greater level of heat pump operating dynamics, and a differentiation between heat pump types (e.g. ASHP and GSHP) and sectors (retrofit/new build)

4. Academic Studies

One of the key challenges identified in the modelling studies discussed in the last section is the lack of granularity in the data about how heat pumps operate, the factors influencing this, and their relative impacts. Ultimately, answering DECC's question on the optimum ways to use heat pumps for peak shifting, will require a combination of modelling studies to provide broader brush conclusions, and more granular studies to provide evidence on the dynamics and variability in heat pump operation. This section presents an overview of some of the recent academic literature in this area which goes some way to providing some more granular data at a local level, which could support DECC in answering its key questions.

Modelling groups of heat pumps at a community level

Testing the optimal technology mix which will avoid exceeding the distribution grid capacity: Cooper et al[1] discussed the mixture of heat pumps and micro-generators for a network of 128 homes that would not compromise the existing electricity network. The unique element of this study is its local focus – it ultimately shows that peaks on this local grid can be managed through shifting operating times of a range of local distributed resources including heat pumps. For example, combinations of different heating systems were used in the 128 dwellings (e.g. 64 dwellings with ASHP and 64 dwellings with micro-CHP units) in order to manage the capacity of the local distribution transformer so it is not exceeded,. Building models are based on the University of Strathclyde's ESP-r modelling approaches. Electrical loads are derived from the domestic models developed by CREST at the University of Loughborough. Deployment of micro-generators e.g. solid oxide fuel cells is given as a counter-balance to heat pump deployment. The model which was developed can dynamically simulate the heating and power demands in many dwellings simultaneously, facilitating study of effects which are dependent upon the sum of their power flows. Consideration of the effect of operating conditions includes permutations of climate, control systems (including those which engage with demand side management), grid generation mixes and building properties is also given. Various efficiencies of air source heat pump with/without "minimal" buffer storage are considered as are various efficiencies of micro-generator with/without "minimal" thermal buffer tanks. Insulation improvements have significant impacts on electricity demands, regardless of technology choice. DSM can reduce peak electrical demand.

Simulating heat pump demand profiles: Bagdanavicius and Jenkins[2] simulated heat pump demands via the Hambase building simulation tool for a small community of housing. This study provides good granular data for a short time period though only for ground source heat pumps. Coefficients of performance were derived from manufacturers catalogues. No reference is given to a change in performance over the season but the study only considers one week and therefore COP may not change. Selection of COP leading to power and heat demands is a critical element. On-Off control was utilised for the heat pumps. Dedicated storage is not considered although hot water cylinders are incorporated. There appears to be a general consideration of start characteristics and therefore the total demand of 34 GW for space heating for the UK housing stock does not appear to have a timing constraint placed upon it.

---

[1] Samuel J.G. Cooper, Geoffrey P. Hammond, Marcelle C. McManus, John G. Rogers (2014) Impact on energy requirements and emissions of heat pumps and micro-cogenerators participating in demand side management Applied Thermal Engineering, In Press, Corrected Proof, Available online 4 January 2014

[2] Audrius Bagdanavicius, Nick Jenkins (2013) Power requirements of ground source heat pumps in a residential area Applied Energy, Volume 102, February 2013, Pages 591-600

Modelling heat pump technology characteristics

Start-up and shut-down characteristics were investigated by Uhlmann and Bertsch (2012)[3]. The shut-down/start-up characteristics appear quite short and therefore imply that that they refer to cyclic operation. In such circumstances the heat pump system is believed to be warm, thus meets thermal demands relatively quickly. The results show that this is very dependent on the type of installation and style of operation. For example, a buffer tank will ensure a more rapid heat up time than a heat pump without a buffer tank. Thermal comfort expectations are then more easily met. Furthermore heat pumps supplying lower temperature underfloor heating systems operate over longer periods at reduced power consumption rather than a heat pump operating with higher temperature radiators which may operate more like a boiler.

Performance: Kelly and Cockcroft[4] modelled the performance of an ASHP in a retrofit situation without storage. The study provides granular data at a single household level - it provides some valuable insight into factors influencing heat pump electricity consumption (and therefore grid impact). The dynamics show similar characteristics to that noted by Hewitt[5] of about 30 minutes to reach delivery temperature for an ASHP operating in a similar way to a boiler i.e. on demand heating. Storage is then added by Kelly and Cockcroft and the shifting of electricity demand is illustrated.

URN 14D/256

[3] Michael Uhlmann, Stefan S. Bertsch (2012) Theoretical and experimental investigation of start-up and shutdown behaviour of residential heat pumps International Journal of Refrigeration, Volume 35, Issue 8, December 2012, Pages 2138-2149
[4] N.J. Kelly, J. Cockroft (2011) Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data Energy and Buildings, Volume 43, Issue 1, January 2011, Pages 239-245
[5] Neil J Hewitt (2012) Heat pumps and energy storage – The challenges of implementation Applied Energy, Volume 89, Issue 1, January 2012, Pages 37-44