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DOI:

[10.1016/j.energy.2018.02.079](https://doi.org/10.1016/j.energy.2018.02.079)

Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Clegg, S., & Mancarella, P. (2018). Integrated electricity-heat-gas modelling and assessment, with applications to the Great Britain system. Part I: High-resolution spatial and temporal heat demand modelling. *Energy*.
<https://doi.org/10.1016/j.energy.2018.02.079>

Published in:

Energy

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Integrated Electricity-Heat-Gas Modelling and Assessment, with Applications to the Great Britain System. Part I: High-Resolution Spatial and Temporal Heat Demand Modelling

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Abstract

The heating sector is a major contributor to greenhouse gas emissions in most countries, and in the UK in particular it accounts for around 20% of carbon emissions. Therefore, various scenarios have been proposed to decarbonise heating. However, studies in this direction do not typically consider the tight interactions with the electricity and gas sector in a multi-energy system context, nor the required geographical and time resolution. To bridge this gap, a novel high-resolution spatial and temporal integrated electricity-heat-gas model has been developed to assess the impact of low-carbon heating options on electricity and gas transmission networks with the consideration of heat demands requirements. The presentation of this modelling is provided in a two-part paper. By using building simulation software and statistical information, Part I, presented here, develops a model for the seasonal and intraday heat demand at half-hourly intervals for 404 areas across the whole of Great Britain (GB). Modelling of different heating technologies has then been used to map the equivalent impact on electricity and gas regional supplies. Model validation is performed by comparing results against historical gas consumption data and shows that fuel consumption can be evaluated to within a 3% accuracy. The numerical studies highlight the importance of high-resolution modelling to capture peak and asset requirements. In particular, the results show how the half-hourly peak heat demand can be around 200% greater than the mean daily heat demand. In the companion paper, Part II, the developed heat demand model is then applied as an input into a novel integrated heat, gas and electrical transmission network model that addresses questions concerning potential future infrastructure impacts and requirements upon changes to the heating sector.

Key words:

Heat demand modelling, multi-energy systems, integrated energy systems, combined heat and power, electric heat pump, gas boiler, gas demand.

1 Introduction

For many regions, heating and cooling requirements represent a substantial factor in the total energy needs. Hence, in countries such as the UK, where heating is dominated by natural gas [1], significant changes may be needed to achieve the challenging environmental targets set out by the Government (for instance, achieving 80% of UK total energy supply from renewables by 2050 [2]). While the clarion call for changes in technologies of the heating sector as a means of reducing its carbon impact is well-founded [3], the knock-on effects on the gas and electricity sectors has achieved less attention. However, in most cases, electric heat pump (EHP) and combined heat and power (CHP) technologies are likely to play a key role in decarbonisation paths, and both may impact both electricity and gas infrastructure to different extents. Whole-energy system studies based on multi-energy system modelling [4] are therefore needed to truly assess the impact of low carbon futures on the energy business and infrastructure. However, studies in this direction do not typically consider the impact of future options on transmission network infrastructure. In spite of this, in countries with cold winters and a large heat demand, which in the case of Great Britain can reach over 5 times the daily electrical demand, changes to the heating sector's technologies can have dramatic effects on the electricity and gas networks. In addition, especially where the heating sector is dominated by natural gas, there is a limited amount of raw data as to the within day heat demand, as the gas consumption of a given consumer is often only recorded daily or biannually. A prerequisite for the successful assessment of changes in the heating sector and their infrastructure impact is therefore the modelling of heat demand which includes the substantial within day variations. This is particularly critical to study impacts on peaking requirements of the electricity infrastructure, as well as on intra-day storage availability and flexibility of the gas infrastructure [5].

Prior research into bottom-up modelling of heat demands have considered dwelling characteristics to assess the system domestic heat demand for the UK [6] and the impact of insulation changes on carbon emissions. Methods based on the characteristics of buildings are also used in [7] where the half-hourly heating demand was modelled for the UK. These methods were applied in [8] to assess the economic benefits of certain heat technology changes and in [9] to assess the benefits of flexible heat demand to the power system. In [10] historical daily gas and electrical consumption data for the GB system were used to assess the impact of heat technology changes on the daily system demand. However, nowhere has the impact on multi-energy network flows and infrastructure been considered thereby allowing for the inclusion of an assessment of different low carbon heating technologies. In [11] the authors developed techniques for the study of the impact of possible future electricity-and-heat scenarios on interactions and operation of the gas and electrical network, but the changes in heat demand were only considered at a system level, without regional resolution, and for a limited number of technologies. While in [12], hybrid heating technologies (those with more than one means by which heat may be generated) were shown to reduce the installed capacity of conventional generating units and reduce the system investment costs, although without the assessment as to any impacts or benefits to the gas and electricity networks. A number of previous studies (e.g., [13] [14]), have developed techniques for the combined modelling of gas and electrical networks though without consideration of the heat demands. While in [15], where gas and electrical network

modeling is considered, the change in the system peak electrical demand due to heat technology changes is evaluated, this was done without integrating the impact on gas flows for heating and the consideration of regional variations.

This work is the first to consider the intraday heat demands for buildings at regional basis. This allows the development of a nodal heat demand model with heat demand areas discretised into points that can be mapped to localities of multiple energy system infrastructures, including electrical network buses and gas network offtakes. Each such node is associated with distinct half-hourly time series of fuel demand for the heating sector. Such temporal resolution is appropriate for power system modelling where the order of magnitude of each interval coincides with the duration of the intraday energy markets for which power system dispatch and unit commitment are performed. This allows for investigation into the effects of different low carbon electricity-and-heat options, in an integrated analysis, specifically considering the interdependencies between, and impacts on, the electrical and gas networks. This is carried out by bottom-up modelling, whereby the system-level heat demand is obtained by the aggregation of the heat demand of individual commercial and residential buildings at half-hourly resolution. Such building-level heat demand evaluation considers space heating (SH) demand based on structural models of building energy consumption (through the EnergyPlus simulation tool [16]), as well as domestic hot water (DHW) consumption based on statistical information. The results of the aggregated system demand model are validated through historical gas demand information. Together with historical electricity consumption information, the modelled half-hourly heating consumption is then mapped onto the electricity and gas network nodal demands based on the considered heating technologies' conversion characteristics for given scenarios. In Part II [17], the resulting heat demands are included into an integrated gas and electric network model so that the impact of heating on system energy flows may be evaluated. This model is used in the analysis of the progression of the electricity and heat sectors towards a low carbon energy system. The analysis includes an evaluation of the annual utilisation factors of the gas and electricity networks, also considering their associated system costs and emissions. Additionally, the potential for hybrid heating technologies to reduce electrical peak demands and alleviation of gas network constraints is shown. Finally, case studies also assess the resilience of the gas network to extreme weather and gas supply shocks.

The application of the methodology to the British system, including the model's verification against gas consumption, shows how such methods may be applied to assess the impacts of different heating decarbonisation scenarios and inform on a number of policy issues. In particular, the regional breakdown of the heat demand and heat technologies is important to assess the end-use of energy in a given region. This can inform on the sectors of greatest carbon intensity and, for example, allow a regional focus in the allocation of funds to reduce the carbon impact. In this respect, a number of pathways for the British system are presented in Part II, in which alternative regional approaches to decarbonising the heating sector are considered. The analysis provides an assessment of the operating cost reductions associated with the electrification of the heating sector and the decarbonisation of the electricity sector. Furthermore, it is shown how hybrid heating technologies, in addition to reducing the operating costs of the system as the cheapest fuel is used for heat production, may also contribute to gas network congestion relief and integrated system resilience. Finally, gas network study results show how nodal gas prices can influence the development of the heating sector.

This paper is organized as follows. Section 2 discusses the development of the intraday heat demand models for different buildings and their use in the development of a heat profile for a given region. Section 3 discusses the development of a nodal heat demand model for a

country, the integration of the intraday profiles of Section 2, and the development of correspondences between the outside temperature and the heat demands. Section 4 applies the models developed to case studies for the GB system and includes a validation to the simulation results. Finally, Section 5 gives conclusion and bridges into the companion paper.

2 Intraday heat demand modelling

2.1 Generalities on the heat demand modelling capabilities

A set of specific models have been developed for the assessment of the changes in the heat demand requirements at different times of the day. These consider the heat requirements of a range of prototypical buildings with different characteristics (Sections 2.2–2.4). The range of prototypical buildings considered can be tailored to the energy system to which the modelling is applied. However, to exemplify a potential classification, Appendix A presents the classes considered for the application here in case studies based on the British system. The resulting profiles are then combined with the use of aggregating factors to assess the intraday heat demand requirements of a collection of buildings (Section 2.5). The various building characteristics considered allow for the model to be applied to diverse types of heat demand which may occur in different districts of a country as well as to alternative nations and power systems. For example, the consideration of distinct residential, commercial and industrial buildings allows for an assessment as to the different heat demand requirements for areas with markedly different heat requirements. Furthermore, the consideration of a number of different building types allows for the models to be used in, for example, the assessment of the changes in requirements due to the effects of ongoing programs to improve the levels of insulation in different regions. The domestic models depend on the times at which the occupants are at home and so are able to consider alternative living styles (for example, schemes to encourage employees to work from home).

2.2 Space heating requirements of buildings

Heat demand is a dynamic process. A greater rate of energy is required to heat or cool a building as compared to maintaining a constant temperature. It is therefore necessary to consider models which include the dynamic nature of temperature change, energy transfer through the exterior of the building (walls, windows, doors, etc.), latent heat capacity of furnishings, temperature differences between rooms within a building, etc. The consideration of the building's interior, even though highly simplified, captures, for example, the different rates of heat demand requirement between upstairs and downstairs rooms as the upstairs rooms can suffer from heat losses through the roof in addition to the walls (each with differing heat-loss coefficients). The modelling of this has been achieved in this work by the dynamic heat models provided by the EnergyPlus software package [16]. This allows for the successful modelling of a property's heat requirements at half-hourly intervals. If the temperature inside the building is $TI(t)$ at time t , at first approximation the change in internal temperature dTI/dt , depends on the outside temperature $TO(t)$, the temperature of the building structure $TM(t)$, and the rate of heat supplied to/withdrawn from the building. While EnergyPlus adopts much higher level differential equation modelling, these may be simply and basically related by a set of two differential equations, with equivalent constants depending on the building [18].

In the modelling, the required internal target temperature time series $TT(t)$, $0 \leq t < 24$, are combined with the outside temperature time series, $TO(t)$, and the building

characteristics¹ BC , to produce, using EnergyPlus, the rate of energy demands time series for a day. This is denoted by $D_{BC,TO,TT}(t)$, $0 \leq t < 24$.

An individual building has a number of characteristics. If it is a commercial building, the floor space and insulation level are dominant factors in its total heat demand, while if the building is residential, influencing factors include its type (flat, detached, semi-detached, terraced) and the number of bedrooms.

2.3 Temperature requirement profiles

The temperature requirement for a building depends on the occupancy patterns; for example, commercial buildings are, in general, only heated during the day for normal office hours. For a given day, whether the temperature of a building is to be heated to a required temperature is modelled with a binary variable called the *set-point activation variable*. This variable takes 1 when the building is heated to the *set-point temperature*. The other times of the day the building is heated to the specified *set-back temperature* and the set-point activation variable takes 0.

For a residential property the set-point times depend on the occupant's lifestyle pattern, that is, it is activated at times, during daytime, when the occupants are at home. These follow the occupancy pattern of a "typical working adult". For a working day, the times when the set-point is activated depends on the occupant's morning wake-up time and the time at which they return to their home in the evening. While, for a holiday/weekend, there is a distinct set-point activation profile which depends on the occupants' wake-up time for these days. The set-point temperature is the desired home temperature at these times.

There is also a temperature associated with the set-back time. In colder climates, it is common for people to set their heating at lower temperatures during these times. This can be, for example, to warm the residences overnight, or, as is common, to continue to use the heating, even when the home is unoccupied, so as to prevent frost damage to the heating system.

For commercial buildings, the set-point activation times depend on the working hours and opening times.

The set-point and set-back temperatures additionally depend on the season, depending on whether the occupant requires property to be heated or to be cooled.

If d denotes whether the profile refers to a working day or a holiday/weekend, then the set-point activation profile is denoted by $SP_d(t)$, $0 \leq t < 24$ such that, for each time t , $SP_d(t) \in \{0,1\}$. Then for set-point temperature T_S and set-back temperature T_B , the required indoor target temperature $TT_d(t)$, $0 \leq t < 24$ is described by

$$TT_d(t) = \begin{cases} T_S & \text{if } SP_d(t) = 1, \\ T_B & \text{if } SP_d(t) = 0. \end{cases} \quad (1)$$

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¹ The notation BC is used to denote the set of characteristics which define the model of the building used as inputs into EnergyPlus. These characteristics include the number of rooms, the function and floorspace of each room, the number of floors, U -value of the internal and external walls (defining the buildings construction material and insulation levels), etc. (Appendix A presents potential building characteristics which may be considered for the application to the case studies based on the British buildings stock).

2.4 Domestic hot water modelling

The energy demand for domestic hot water can be a sizable fraction of the overall demand for heating. In particular, for the UK, it corresponds to approximately a third of domestic heating demand [19].

Previously derived historical statistical sample sets for individual dwellings can provide data on the volumetric daily hot water demands, the hourly breakdown of how water usage in homes, and the temperature requirements for hot water for washing. In particular, for a given home, a key factor in the volumetric domestic hot water consumption is the number of occupants; in this respect, the historical data allows deriving a relationships between the number of occupants and the volumetric demand [20].

So that, for a collection of typical homes with a occupants let W_a be the mean volumetric daily hot water demand. Given an intraday profile $W(t)$, $0 \leq t < 24$ for the volume of hot water consumed by domestic homes in a region, then the average volumetric demand for a typical home with a occupants is described by $W_a(t) = W_a \cdot W(t) / \int_{0 \leq t < 24} W(t) dt$, $0 \leq t < 24$.

The energy requirements for heating the water are evaluated with consideration of the temperature difference and the water's calorific value. This considers the washing temperature, which, again, may be derived from statistical surveys, and the pipe inlet temperatures. The outside temperature, affecting the temperature of the water in the inlet pipe water, leads to variations in the heat demand required for the water to be heated to the desired temperature. Different inlet temperatures are therefore considered for different seasons. For a given volumetric flow rate, the energy required to raise the water temperature to that desired is considered. If θ_{in} is the water's inlet temperature, θ_{out} the desired water temperature and C_q is the specific heat capacity of water, then, following [21], the average demand for a typical home with a occupants is given by

$$DHW_a(t) = W_a(t) \cdot C_q \cdot (\theta_{out} - \theta_{in}) \quad (2)$$

for $0 \leq t < 24$.

2.5 Domestic space heating and hot water requirements for a number of households: diversity and regional modelling

In summing the heat demand for individual residences into that for a region time diversity factors have been considered. As discussed, the target internal temperature, and hence heat demand profile, for individual residence is affected by the occupants' lifestyle patterns. The dominant factor as to what hours of the day the home is heated is the wake-up time of the home occupants. For a given region, the pattern of wake-up times, i.e., the fraction of households who "wake" at a given time, can be described in terms of the number of occupants. These are then used as a means to introduce diversification to the heat demands of individual homes and form a daily space heat and hot water demand profile for a given region. This process can be formulated as follows.

To each household is associated a wake-up time w , which depends on the day of the week and whether the day is a holiday. At first approximation, its heat profile for this day has been determined with respect to the wake-up time by time shifting a typical household daily heating profile, for the same day, with a wake-up time of w' . So that, if $TT_{d,w'}(t)$ is the time series for the internal temperature requirements of a household with typical wake-up time w' on day d and its energy demand profile is $D_{BC,TO,TT_{d,w'}}(t)$, $0 \leq t < 24$, where t indexes the time of the day, then the heat demand at t for a household with wake-up time w is modelled by

$$HH_{BC,TO,d}(w, t) = D_{BC,TO,TT_{d,w'}}([t - k \pmod{24}]) \quad (3)$$

where $k = w - w'$ is the difference between the wake-up time for the household and the wake-up time in the typical profile.

A key indicator as to the wake-up pattern of a house is the number of occupants. So, the distribution of wake-up times for homes with building characteristics BC and a occupants is described by $\omega_{BC,a}(w)$, $0 \leq w < 24$, so that $\int_t^{t+\Delta t} \omega_{BC,a}(w) dw$ represents the fraction of such households who wake between time t and $t + \Delta t$. Then, in determining the space heating requirements for buildings in a region for a given day, the profiles for different occupancy levels are combined with given building characteristics and the number of such buildings in a region. In particular, if N_{BC} is the number of homes in the region with building characteristics BC , and $\phi_{BC,a}$ is the fraction of these homes with a occupants, then their heat demand $HD_{BC,TO,d}(t)$ at time t , $0 \leq t < 24$, in the day is given by

$$HD_{BC,TO,d}(t) = N_{BC} \sum_{a=1,2,\dots} \phi_{BC,a} \cdot \int_0^{24} \omega_a(w) \cdot HH_{BC,TO,d}(w, t) dw \quad (4)$$

The DHW demand, WD_{BC} , for a collection of homes of a given building characteristics is, again, assessed with consideration of the fraction of homes with a given number of occupants so that

$$WD_{BC}(t) = N_{BC} \sum_{a=1,2,\dots} \phi_{BC,a} \cdot DHW_a(t) \quad (5)$$

The heat requirements for homes in a given region is modelled by summing (4) and (5) over the possible building characteristics BC .

2.6 Commercial and light-industry space heating for a number of premises

The total space heat demand for a region for the commercial and industrial sectors has been calculated in terms of the total floor space for a given end-use class. The calculation considers the heat demand of individual commercial and industrial buildings, including their distinct intraday profiles resulting from the different end-uses and temperature set-point and set-back requirements.

More specifically, for a given building characteristics which are dependent on the primary building purpose (office, warehouse, retail, factory), and given insulation level (for example, categories such as “Poor”, “Medium”, and “Good” have been used for the archetypes considered in this work), the total floor area for this type in a given region R_{CB} is considered [22]. If the typical buildings' floor area is given by FL_{CB} and has energy requirements determined by EnergyPlus as $CD_{CB}(t)$, $0 < t \leq 24$, then the total space heat demand for the commercial and light-industry sectors $CD_R(t)$ for a given region R is given by

$$CD_R(t) = \sum_{CB} \frac{R_{CB}}{FL_{CB}} CD_{CB}(t) \quad (6)$$

3 Nodal heat demand model and gas and electrical network interactions

To assess the half-hourly nodal gas and electrical usage required to meet the heat demand a number of considerations need to be included. A ‘nodal’ model of the heat demand has been developed so that each region of heat demand can be associated with an offtake on the gas

network and/or a bus of the electrical network (these are seen ‘nodes’ in the gas and electrical network model, respectively). As well as developing this spatial heat demand characteristics, there is a need to introduce correspondences between the day-to-day temperature variations and the heat demand. The nodal heat demand for each half-hour can then be used with characteristics of the heat producing technologies to determine the nodal electrical and gas demand for heat demand.

3.1 Nodal heat model

The forming of the nodal heat model considers regional temperature variations and uses available statistics to form the nodal heat demand. Firstly, each region has an associated outside temperature profile $TO(t)$ which is defined by its temperature zone (e.g., North, Central, South) and the season (e.g., winter, midseason and summer) and is used as an input in the formation of heat demand profiles for the typical buildings in the given region, as discussed in Section 2.1. Statistics on the breakdown of the type and insulation levels of homes and the number of occupants as well as on the floor space and age of commercial and industrial buildings allow for the determination of aggregated heat profile for the region. For a given sector U (domestic, commercial or industrial), let $HD_{U,S,R}(t)$ be the heat demand for region R and season S . For the commercial and industrial buildings, consideration of the age of the building can be used as an indicator into the space heating demand and allow for the grouping of the buildings into categories [23]. For example, in the construction of more modern buildings there are greater incentives to use building materials which reduce the heat demand. Such incentives include the reduction in fuel usage and costs, potential subsidies, as well as increased regulation in the building sector. The insulation level of a given commercial and industrial building has therefore been characterised by its age.

The effect of changes in the heating sector on the electrical and gas transmission networks is assessed, as the heat fulfilled by one network may be shifted, under a change in technologies, to being supplied by the other. Also, in the case of CHP, electricity injection and therefore reduced electrical consumption for a specific node may arise from local heat supply. The correspondences for these changes has been developed using a nodal heat map describing, at a nodal level, the heat demand for a given region for each sector. The heat nodal demand is constructed so as to have a finer granularity and to allow for maps to be defined from the heat demand nodes to the gas nodes and to the electrical buses. This ensures that a given heat node has its gas and electricity requirements fulfilled by exactly one node of the gas and one bus of the electrical networks.

A given region may contain a number of nodes. Each node n has its annual heat demand for the residential, commercial and industrial sectors described by statistics. The profiles for each region are split into the nodes in a given region. Let us consider $AH_{U,n}$ as the annual heat demand for node n for the sector U . Therefore, if N_R is the collection of nodes n in the region R , the heat demand for node n , sector U and typical day of season S at time t ($0 \leq t < 24$) is given by

$$HD_{U,S,n}(t) = HD_{U,S,R}(t) \times \frac{AH_{U,n}}{(\sum_{n' \in N_R} AH_{U,n'})} \quad (7)$$

Accordingly, for each season S , the system’s total demand profile $V_{U,S}(t)$, $0 \leq t < 24$, for the sector U is obtained by summing the profiles for each of the nodes, i.e.,

$$V_{U,S}(t) = \sum_{n \in N_S} HD_{U,S,n}(t) \quad (8)$$

where N_S indexes the nodes in the system.

3.2 Relation between the outside temperature and the heat demand for a day

For a given day, the total heat depends primarily on the outside temperature along with whether the day is a working or weekend day. Analytic relationships between the average daily outside temperature and the daily gas demands may be extrapolated to assess the heat demand. In this respect, to assess the heating sector's daily gas consumption, the gas consumers are split into two categories, namely, those for which space and water heating dominates the end-use of gas, and those for which the gas is principally used for other purposes. The latter category includes gas consumers with direct offtakes from the gas transmission network e.g., power stations and industrial facilities for which gas is used as part of an industrial process². Because, for the latter category, factors other than the outside temperature contribute to the majority of the gas demand (e.g., for power stations, the gas demand depends on the power system requirements), then only the gas demand for the first category of consumers met through the gas distribution networks is used for the temperature-related correspondence assessment. In this work, following techniques used in the gas industry [24] and in academic studies [8], this has been modelled with a continuous piecewise linear function with a single breakpoint derived, in the case studies, through the use of regression analysis. This breakpoint represents the temperature threshold T_0 , above which households turn off the boiler for space heating. The model accounts for the difference in demand between a weekday and a weekend day so that, if a day has mean temperature T (Celsius) then its distribution network gas demand, GD_T (TWh) is modelled by

$$GD_T = g(T) + \delta_E \cdot Q_E \quad (9)$$

where g is a piecewise linear function describing the weekday gas demand, Q_E is a constant independent of the temperature, and δ_E is a binary variable taking 1 if the day is the holiday/weekend and 0 if a weekday.

For a given historical daily gas distribution network demand GD_T , historical daily consumption data on the breakdown of usage allows for the allocation of this demand into the domestic, commercial and industrial usage. Letting $\gamma_{U,T}$ be the fraction of the gas demand which is consumed in sector U , then its total gas demand for that day is $GD_{U,T} = \gamma_{U,T} \cdot GD_T$. When a sector's gas demand involves any non-heat gas uses (e.g., cooking or high-temperature industrial and other heavy industry applications), then this is presumed to be consumed at a constant daily rate and subtracted.³ I.e., if NGD_U is the daily non-heat gas demand for sector U , then the gas demand for heating has been modelled by $HGD_{D,T} = GD_{U,T} - NGD_U$. The gas usage for the domestic sector is split further into space heating and hot water requirements. It is assumed that, above the temperature when the boilers for space heat are switched off, all the domestic gas demand is used for hot water requirements so, if $HGD_{D,T}$ is the domestic heating gas demand for a day with average daily temperature T , then the domestic hot water has been modelled by

² It is assumed that any gas-based space or water heat demand associated with these large industrial offtakes remains gas-based under nationwide changes in heating sector technologies; therefore, the fuel demands are unaffected.

³ In the assessment of the total gas demand performed in Section 4.7 and in Part II, the evaluated gas demand for the heating sector is combined with the gas demand for other uses (based on historical profiles) to assess the total gas demand. In Part II, the evaluation additionally considers the gas demand for power stations which has been assessed using power system modelling.

$$HGD_{DHW,T} = \begin{cases} HGD_{D,T_0} & \text{if } T \geq T_0 \\ HGD_{D,T} & \text{if } T < T_0 \end{cases} \quad (10)$$

371 And the domestic space heating by

$$HGD_{SH,T} = \max(0, GD_{D,T} - GD_{D,T_0}) \quad (11)$$

372 If for a given sector the fraction of heat demand which is fulfilled through natural gas is ψ_U ,
 373 then the overall heat demand for a day may be modelled by $HD_{U,T} = HGD_{U,T} \cdot \eta_B / \psi_U$
 374 where η_B is the mean thermal efficiency of gas boilers.

375 Finally, temperature dependent half-hourly nodal heat demands for each sector are formed
 376 by scaling the profiles for typical seasonal days with the changes in system heat demand due
 377 to variations in the average daily temperature T . So that, for the heat node n , and sector U ,
 378 the half-hourly heat demands for a day with average temperature T lying within the season
 379 S is

$$HD_{U,T,n}(t) = HD_{U,S,n}(t) \times HD_{U,T} / \int_{0 \leq t < 24} V_{U,S}(t) dt \quad (12)$$

380

381 3.3 Heat technologies

382 The heat demand at each node for each sector is fulfilled by the specific heat generating
 383 technologies. The heat technologies available in each scenario also depend on the node's
 384 locality as well as the sector and end-use of the heat.

385 In the first instance, the considered technologies may be categorised by those which serve a
 386 community, e.g., community-scale CHPs developed to meet the heat demand and produce
 387 electricity for the grid, or, alternatively, the utilisation of cogenerated heat from large-scale
 388 power stations which may have to be transported long-distances to the localities of the heat
 389 demand. Often, the heat available from these sources is limited by their capability and when
 390 the heat demand is above that which may be met by this source, then the heat must be
 391 supplemented by alternative means (e.g., using a gas boiler, or through resistive heating).
 392 Therefore, the winter heat demand can be considered in terms of that which is fulfilled by
 393 *base-load heat* generating units (e.g., community-scale CHPs, and heating from power
 394 stations) and the remaining heat demand which is fulfilled by *heat following* technologies.
 395 The amount of heat which is fulfilled by the base-load heat technologies at each node is
 396 constant for each time of the day while the remaining heat demand is required to be met by
 397 heat following technologies. These heat following technologies supply the remaining heat
 398 demand in a fixed proportion depending on the levels of installation for the node.

399 For the purposes of this work, we define the thermal efficiency (or coefficient of
 400 performance (COP) in the case of EHPs) of a given technology as the ratio of heat produced
 401 to fuel consumption. The heat demand for each node is fulfilled by a number of distinct heat
 402 technology units in individual homes and/or commercial and industrial buildings. While the
 403 individual operation of each heat producing technology (e.g., their part-load operation or
 404 switching on/off to follow temperature set-points) may vary, for the sake of simplicity the
 405 thermal efficiency is assumed to be fixed over the half-hour simulation periods considered
 406 here. The efficiency of gas boilers, resistive heating, gas heat pumps, and CHP is also
 407 considered independent of external temperature, while the COP of air-source and ground-
 408 source EHPs is modelled as dependent on the outside air and ground temperatures,
 409 respectively. The CHP units are also characterized, besides their thermal efficiency, by their
 410 electrical efficiency.

Upon evaluation of the utilisation rate of each heat technology for a given heat technology penetration level, the gas consumption and electrical consumption and generation is determined for each heat node. Each heat node is associated with a unique electrical bus and gas network node from which the fuel is sourced. The changes to the electrical and gas requirements between the technologies are therefore mapped into a change in a gas and electrical demand requirements at the gas nodes and electrical buses on the corresponding transmission networks.

4 Case study applications

The models developed have been applied to case studies based on the British heating requirements and the gas and electrical networks. The heat demand considers a 404 node model while the gas and electric flows are modelled on a 79 node and 29 bus model, respectively.

While the modelling has been applied to, in the accompanying paper [17], an assessment of the system impacts of changes in the heating sector, here, the focus is on the development of the implementation of the modelling for the assessment of the heat demand of the British system along with the validation of the results of the process which have been compared against historical gas demand data.

The domestic buildings have been characterized using a number of factors. The type of residence is classified as detached, semi-detached, terraced or flats while the level of insulation is assessed using statistics on the Energy Efficiency Rating [24] [25] for each category. The number of house occupants gives an indication as to the size of the house, number of rooms, etc. These factors are used to determine the constants defining the building characteristics BC (the precise breakdown of the building classes considered are summarised in Appendix A) which are inputted into EnergyPlus.

The commercial buildings have been characterized by their facility and their age. A generic building is used for a building with primary use as an office, warehouse, retail or factory. As mentioned in Section 3.1, the age of the building gives an indication as to its thermal efficiency and insulation levels. The building's age has been classified as Old, Modern or New, those built prior to 1944 are designated 'Old', those built 1945–1984 are called 'Modern', and those which were built in 1985 or later are called 'New'.

4.1 Domestic hot water

Using historical samples, [20] records the volumetric quantity and DHW consumed for 120 UK households. Furthermore, analytic relationships were derived and presented to describe the relations between the volumetric consumption and the number of residents and daily consumption profiles.

If the number of occupants is $a = 1, 2, \dots, 5$ or more than 6, then the volume of water consumed, W (liters/day) is given in [20] by $W_a = 46 + 42a$. The water inlet temperature θ_{in} depends on the ground temperature which can vary according to the season and hence the temperatures from Figure 1 are used according to the day of the year. A desired hot water temperature of $\theta_{out} = 52^\circ\text{C}$ is assumed. Using the specific heat capacity of $C_q = 4.19$ kJ/(litres·K) the domestic hot water for given days are evaluated using (5).

Figure 1. Ground and inlet hot water temperature [20]

4.2 Domestic heating data

For the “typical working adult” it is presumed that, on a working day, the heating is turned on a half-hour prior to their wakeup time w_W and remains on for an hour after the wakeup time. On their evening return at time r , the home is heated from their return until the time they retire for the evening, presumed five hours after their return time. So the temperature set point binary variable at time t is given by

$$SP_W(t) = \begin{cases} 1 & \text{if } t \in \left[w_W - \frac{1}{2}, w_W + 1\right] \cup [r, r + 5], \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

For the weekend/holidays, the set-point activation times depends on the weekend wakeup time, w_H

$$SP_H(t) = \begin{cases} 1 & \text{if } t \in [w_H, w_H + 16] \\ 0 & \text{otherwise} \end{cases} \quad (14)$$

It is assumed that the desired heating set-point and set-back of residences is 18°C and 12°C, respectively [9].

For the EnergyPlus modelling from which the heat demand is determined, the wake-up time is 7am (for both weekdays and weekend/holidays) and the evening return time is 6pm. Daily heat demand requirements are obtained for a number of building characteristics (dwelling type, insulation level, etc) [26]. For illustration of the results of the EnergyPlus modelling, the space heat demand for alternative types of homes with Poor insulation in the North for weekday is shown in Figure 2. Similarly, a comparison of the weekday heat requirements to those at the weekend can be seen in Figure 3.

Figure 2. Results of EnergyPlus modelling for space heat demand requirements for alternative types of homes with Poor insulation in the North, with a wake-up time of 7am and evening return time of 6pm for a Typical Winter Day

Figure 3. Results of the EnergyPlus modelling for the heat demand requirements for semi-detached home with Poor insulation in the North, with a wake-up time of 7am and evening return time of 6pm for the weekday/weekend on a Typical Winter Day

4.3 Commercial and light industrial space heating data

The set-point activation periods of the typical commercial and light industrial buildings align with their working hours and opening-times. These are described in Table 1 along with the set-point and set-back temperatures and floor space which are used as inputs into the EnergyPlus software [27].

Table 1 Set-point activation times and temperatures

	Opening times			Set-point (°C)	Set-back (°C)	Floor space (m ²)
	Monday-Friday	Saturday	Sunday/Holiday			
Office	0800–1900	Close	Close	22	12	1112
Retail	0900–2100	0900–2100	0900–2100	20	12	87
Warehouse	0700–2100	0700–1900	1200–1800	18	12	773
Factory	0700–1900	0900–1400	Close	19	12	823

Typical results from EnergyPlus modelling for the weekdays are shown in Figure 4.

Figure 4. Space heat demands for alternative commercial and industrial building uses with Poor insulation in the North with for a weekday on a Typical Winter Day

4.4 Determination of nodal heat demand

The type of housing (detached, semi-detached, terraced, flats), dwelling age and the number of occupants per household for the 11 UK mainland regions are described in the housing surveys [28] [29] [30]. The commercial buildings are described in [31] [32]. It is assumed that, for a given region, the breakdown of housing types and the age of the housing are independent. Following [33], the wake-up profiles for each region have been derived from statistics of lifestyles, working hours and the number of home occupants. The wake-up profile for one such region is shown in Figure 5.

Figure 5. The morning wake-up times for households for a weekday in the North East region

After the inclusion of the time diversity factors, the sectors heat requirements for each region are determined while considering the different building characteristics. Figure 6 gives an example of such a heat demand for the weekday and weekend.

Figure 6. Domestic space heat demand for the North East region for a Typical Winter Day

The nodal heat demand has been modelled with each node being represented by each of the UK mainland local authorities (Figure 7(a)) so as to provide a detailed model to assess impacts on the gas and electrical transmission networks.

Figure 7. UK mainland local authorities, each of which constitutes one of the 404 heat nodes (a); 79 node gas (b) and 29 busbar electricity (c) models of the GB transmission networks (elaborated from [34])

Each local authority lies within a single UK region, for which the breakdown of households is described and which has been used in determining the heat demand for the local authority. The proportions of the heat demand which arise from each node is described by the DECC Heat Map [35] which gives statistics on the annual heat demand. Each of local authority has

its historical annual electrical and gas consumption recorded in [19]. Based on this consumption data, the historical demands for the gas and electrical network model's nodes, and locality of the transmission network offtakes and distribution network configurations, each local authority region is associated with one of the 79 nodes of the GB gas network model (Figure 7(b)) and one of the buses of the 29 bus electrical model (Figure 7(c)).

4.5 Determination of the GB daily heat demand and the temperature correspondence

Figure 8 shows the historical relationship between the gas distribution network demand on a working day and the mean outside temperature. As described in Section 3.2, this data has been used to form a piecewise linear correspondence between the mean temperature of a day and the gas consumption.

Figure 8. Historical distribution network gas demand against the mean temperature using data from 2011–2014. The resulting relationship for modelling the correspondence between this gas demand and the temperature is displayed with error bars describing its root mean square error

In the formation of this relationship, it is assumed that the temperature at which the boilers for space heating are turned off is $T_0 = 15.5$ Celsius [8]. For a mean daily outside temperature T (degree Celsius), the gas distribution network demand for heating, GD_T (TWh), on a day with this temperature is modelled by

$$GD_T = \begin{cases} 3.43 - 0.17T + \delta_E \cdot Q_E & \text{if } T < 15.5 \\ 1.10 - 0.02T + \delta_E \cdot Q_E & \text{if } T \geq 15.5 \end{cases} \quad (15)$$

where, as mentioned Section 3.2, δ_E is a binary variable taking the value 0 if the day is a working day and 1 otherwise, and the effect on the gas demand of whether the day is working day or not is described by $Q_E = -0.13$ TWh. The root mean square error of the model is 0.23 TWh.

For a day with a given gas demand, its breakdown into sectors is described by the gas forecasting dataset [36] and in [37]. Statistics on the breakdown of the end-use natural gas in 2013 are presented in [38] and are combined with historical gas transmission industrial demands to assess the fraction of distribution network gas demand used for heating. The resulting breakdown is presented in Table 2. This is used, as described in Section 3.2, to assess the gas demand for heating and hence the system heating demand for each sector on a given day.

Table 2 Fraction of sector's gas demand used for space heating or DHW in 2013 [38]

Sector	Fraction of gas used for space heating/cooling or DHW
Domestic	98%
Commercial	91%
Industrial	32%

4.6 Heat generation technologies

Using publically available statistics on the number of houses in each UK local authority with a given type of central heating [39] [40] [41], each heat node is associated with a level of heat technology penetration. This allows for the consideration of areas of the country which are not connected to the gas transmission network. Currently, four classes of heat technology dominate the UK heating sector. The gas boilers are the most widespread and are considered to have an average thermal efficiency of 83%, while the thermal efficiency of resistive heating is taken as 100% (as discussed in Section 3.3, these technologies are modelled with a fixed average efficiency). Finally, the oil- and solid-fuel boilers are assumed to have thermal efficiency of 97% and 87%, respectively. The heat technologies from 2013/14 used for the model verification are presented in Table 3.

Table 3 Heat technology penetrations for 2013/14

Technology	Domestic	Commercial and industrial
Gas boiler	88.3%	71%
Resistive heating	6.5%	19.5%
Oil-fired boiler	2.6%	9.5%
Solid-fuel boiler	2.6%	-

4.7 Heating sector fuel requirements and model verification

The half-hourly GB heat demands have been evaluated using historical temperatures from 2013/14. The relevant historical temperatures and resulting system heat demands are presented in Figure 9. For comparison, the mean daily heat demand is also presented. This highlights the need for considering the intraday heating requirements, given that the instantaneous heat demand peaks can be over twice the average demand.

Figure 9. Mean outdoor temperatures for the year 2013/14 and simulated system heat demands derived from these temperatures

If $HD_{U,n}(t)$ is the heat demand for sector U at gas node n , $\psi_{U,n}$ is the fraction of heat fulfilled by gas (Table 3) and η_B is the mean thermal efficiency of gas boilers, then the gas demand for the heating sector in region R is given by

$$HGD_R = \sum_t \sum_{n \in N_R} HD_{U,n}(t) \cdot \psi_{U,n} / \eta_B \quad (16)$$

where N_R is the collection of heat nodes in region R . This demand is included with that from other sectors supplied by the gas distribution network and compared against historical gas sales as a model validation process. The results of this comparison are presented in Figure 10 and, upon comparison at a system level, the simulation results lead to a system gas demand evaluation within 3% of the historical gas sales.

Figure 10. Comparison of model gas demand results with metred gas sales

4.8 Computational aspects

The computational analysis begins with an assessment of the heat demands for the prototypical buildings using the EnergyPlus software package. The analysis for each building was performed individually and the results stored in a database. Databases have also been created for the data associated to the nodal annual heat demands, historical regional temperatures, and the statistics associated with the wake-up times and hot water utilisation. The computations for the British nodal half-hourly heat demand model are then conducted using programs developed in the Matlab programming environment. An annual data set of half-hourly heat demands for the 404 nodes in Britain and for 3 sectors (domestic, commercial and industrial), contains $48 \times 365 \times 404 \times 3 \approx 2.1 \times 10^7$ data points. The recreation of the data set for a given historical temperature profile takes ~ 5 minutes on a desktop PC.

5 Conclusions

A novel system-level high-resolution spatial and temporal heat demand model has been presented which allows for the assessment of the heat demand and fuel requirements at a network and regional nodal level and at half-hourly intervals. The half-hourly variations in the heat demands for each of the 404 considered regions are developed by a bottom-up approach beginning with an evaluation of the heat demands for individual buildings which are then aggregated together to assess heat demand profiles for different regions. These are then combined with an evaluation of the heat demand for a given day, which has been modelled through the development of analytic relationships between the temperature and the heat demand via the consideration of historical gas demand and meteorological data. The fuel required to fulfil the heat demand is then modelled with the consideration of heat generation technology characteristics and alternative levels of penetration of each technology. The resulting model has been verified by comparison with historical gas demand data and can produce results within 3% of historical data. The numerical studies clearly demonstrate the importance of high-resolution modelling to capture peak and asset requirements. In particular, the results show how the half-hourly peak heat demand can be around 200% greater than the mean daily heat demand. In the accompanying paper [17], an integrated heat-gas-electricity transmission network model is presented that uses the high-resolution heat demand model developed here to perform a number of case studies that

address questions concerning potential future infrastructure impacts and requirements in the transition towards a low-carbon heating sector.

6 Acknowledgement

This work was supported by National Grid Gas plc as well as by the UK EPSRC through the “MY-STORE” project (EP/N001974/1).

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Appendix A Building Stock Classifications

This appendix provides data on the characteristics of the prototypical buildings which have been used in the as inputs into the EnergyPlus modelling software for the derivation of the heat demands. For the application of the modelling performed here, each of these buildings has been considered as unfurnished.

Table 4 Characteristics of prototypical residential buildings.

Type				
Detached				
Semi-detached				
Terraced				
Flat				
Number of storeys	2	2	2	4
Number of dwellings per building	1	2	4	8
Dimensions of each dwelling [m]	$7.5 \times 10 \times 3$	$5.5 \times 10 \times 3$	$5.6 \times 10 \times 3$	$7.1 \times 10 \times 3$
Floor area of each apartment [m ²]	152	110	112	71

Table 5 Insulation levels for prototypical dwellings.

	Good		Medium		Poor	
	Summary	U-value [W/m ² K]	Summary	U-value [W/m ² K]	Summary	U-value [W/m ² K]
External walls	Cavity walls with insulation	0.43	Uninsulated cavity walls	1.5	Solid brick walls	2.1
Glazing	High performance double glazing	2.7	Poor performance double glazing	3.3	Single glazing	6.2
Roof	Well-insulated roof space	0.15	Average-insulated roof space	0.75	Uninsulated roof space	2.5
Ground floor	Well-Insulated floorspace	0.25	Average-Insulated floorspace	0.84	Uninsulated suspended timber	1.1

Table 6 Characteristics of prototypical commercial and industrial buildings.

Type	Office	Retail	Warehouse	Factory
Number of storeys	4	1	1	1
Floor area [m ²]	278	87	773	823
Dimensions of each storey [m]	19.3 × 14.4 × 3.6	9.3 × 9.3 × 4.3	27.8 × 27.8 × 7.3	7.1 × 10 × 3
People density [people/m ²]	0.111	0.117	0.0109	0.0225

Table 7 Insulation levels for prototypical commercial and industrial buildings.

		Good	Medium		Poor	
	Summary	U-value [W/m ² K]	Summary	U-value [W/m ² K]	Summary	U-value [W/m ² K]
External walls	Cavity walls with insulation	0.42	Uninsulated cavity walls	0.70	Solid brick walls	3.4
Glazing	High performance double glazing	2.7	Poor performance double glazing	3.9	Single glazing	6.2
Roof	Well-insulated roof space	0.19	Average-insulated roof space	0.42	Uninsulated roof space	2.9
Ground floor	Well-Insulated floorspace	0.32	Average-Insulated floorspace	0.48	Uninsulated suspended timber	1.9