Applied Energy 228 (2018) 965–979

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Assessing the benefits of demand-side flexibility in residential and transport sectors from an integrated energy systems perspective

Pei-Hao Li*, Steve Pye

UCL Energy Institute, University College London, Central House, 14 Upper Woburn Place, London WC1H 0NN, UK

HIGHLIGHTS

- Demand-side flexibility is integrated into an energy systems model (ESM)
- Household appliances and electric cars can provide significant load management.
- By 2050, the peak load can be significantly reduced, with large cost savings.
- ESMs should consider demand-side flexibility as a key mitigation option.

ARTICLE INFO

Keywords:
Demand-side response
Smart appliance
Electric vehicle
Flexibility
TIMES

ABSTRACT

Demand-side flexibility from smart appliances and passenger electric vehicles has been increasingly regarded in recent years as an effective measure to reduce peak loads and to aid system balancing. While numerous studies have been undertaken to investigate the benefits of demand-side flexibility, most have either focused only on the power sector or provided a snapshot for a future year or day. The influence of interactions between sectors in the long-term under energy transition pathways has therefore been under explored. This paper presents a novel modelling approach in a whole energy systems model, UK TIMES, to investigate the benefits of demand-side flexibility from smart appliances and passenger electric vehicles, including the reduction in the costs of moving to a low carbon economy. This analysis shows that demand-side control increases system flexibility, enabling the integration of high levels of low carbon power, such as nuclear and wind, whilst reducing the requirements for storage. By 2050, the peak load is reduced by around 7 GW (9%), and cumulatively about 30.9 billion GBP saved with the help of this demand-side flexibility. This approach could be integrated into other energy systems models to improve the representation of this important flexibility mechanism.

1. Introduction

The UK set an ambitious legally-binding target to reduce greenhouse gases (GHGs) emissions to at least 80% below 1990 levels by 2050 in the UK Climate Change Act [1]. A key option to decarbonise the energy system is the increased electrification of end-use sectors, based on a supply of low carbon electricity. According to estimates [2,3] the level of electricity consumption in 2050 through this push for more electrification could be 50–135% higher than the current level. This increase could impose a serious challenge to delivering sufficient electricity supply while at the same time reducing total GHG emissions from the power sector. Low carbon technologies, such as nuclear, renewable energy and thermal power plants with CCS, therefore need to be deployed at scale. In view of the recent cost reductions for renewables, such as wind turbines and solar PV [4], the system may see increasingly strong deployment of these intermittent generation sources, as the Government also seeks to provide affordable electricity to avoid cost increases to households and other economic sectors. The capacity of such variable renewable energy (VRE) sources could increase to 89 GW, providing about 46% of total electricity generation by 2050 [5]. However, high shares of renewable energy pose significant challenges to a stable electricity system due to their intermittent nature. High wind speed during one period could lead to a surplus of electricity; low wind speed at another period in time could cause a supply deficit.

At the same time, increasing electrification in end-use sectors could lead to higher fluctuations (difference between peak and average demand) across the daily demand profile. This increases the challenge of moving from dispatchable generation to more intermittent or less responsive generation, such as nuclear power. While dispatchable plants, such as gas-fired power plants, and storage systems may need to be

* Corresponding author.
E-mail address: p.li@ucl.ac.uk (P.-H. Li).

https://doi.org/10.1016/j.apenergy.2018.06.153
Received 7 March 2018; Received in revised form 25 June 2018; Accepted 30 June 2018
Available online 06 July 2018

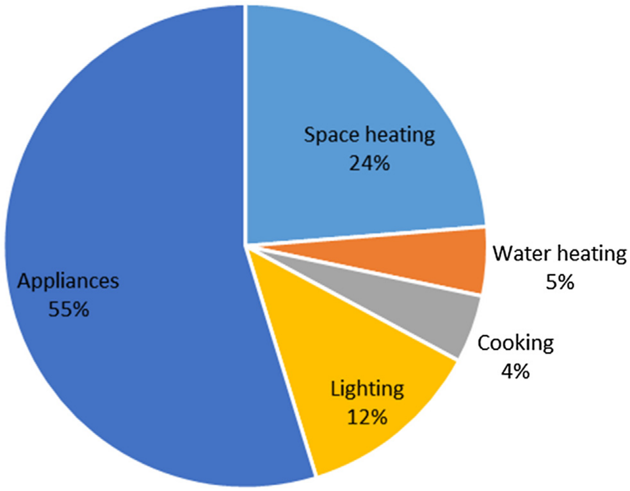

Fig. 1. Electricity consumption by type in the domestic sector in 2016.

deployed to balance electricity supply and demand across short time periods to cope with intermittency, such technologies may be either carbon-intensive or costly.

Demand-side flexibility via demand-side response (DSR) in the end-use sectors is the other promising mechanism to balance the electricity system. For example, with smart controlled appliances in the domestic sector, the electricity load can be shifted or shedded within a short period of time to match the variation in the supply profile of VRE [6–8] or to even out the demand profile to allow for nuclear power on the same system.

In 2016, the UK residential sector consumed 108 TWh, or about 36% of the total electricity demand, the largest share of all end-use sectors [9]. Electricity is consumed to provide a range of energy services including space heating, water heating, cooking, lighting and appliances, as shown in Fig. 1. This electricity consumption could increase dramatically in the future if residential heating were to be decarbonised through electrification using heat pumps (HPs) and electric heaters. Under some projections, the installation of HPs could increase to 16.7 million units [5], or be installed in approximately 49% of households. Similarly, electrification could play a strong role in the transport sector [3], particularly for powering cars and other light duty vehicles, despite currently accounting for only 0.04% (0.13 TWh) of total electricity demand [9].

The projected high electrification level of the residential and transport sectors provides an unprecedented opportunity to significantly increase demand-side flexibility via smart control mechanisms, in order to accommodate low carbon electricity into the future UK energy system, and in doing so reduce energy system costs. In order to exploit these benefits, the UK government plans to roll-out smart meters to every household in the UK by 2020 [10]. The Smart Systems and Flexibility Plan has also been proposed to deliver a smarter and flexible energy system by removing barriers to smart technologies, enabling smart homes and businesses, and making markets work for flexibility [11].

In recent years, numerous studies have been carried out to assess the value of demand-side flexibility. However, most of the studies only consider the impacts on a specific or limited number of sectors, with only partial consideration of path dependency issues or sectoral interactions. No study has yet incorporated demand-side flexibility in a whole energy systems model, where all sectors supplying and consuming different energy types across the system are included, as described in this paper. To date, the complexity of such models has been a barrier to the integration of the dynamics of demand-side flexibility.

To help address this gap, this study aims to develop a novel modelling framework in a whole energy systems model, UK TIMES (UKTM), to assess demand-side flexibility benefits across a long-term energy transition. Despite the temporal resolution of such models being relatively coarse compared to power sector-only models, the variations in demand load can still be captured to a certain level [12,13]. Therefore, this approach has the advantage of capturing dynamics across and between sectors, and can endogenously estimate the techno-economic benefits of demand-side flexibility.

The proposed approach has been applied to specifically explore the potential of demand-flexibility across electricity-using household appliances and passenger EVs, given the prospective increase in electrification. Firstly, the impact of demand-side flexibility on the system-wide electricity supply and consumption is investigated. Secondly, the specific issues related to the deployment of such flexibility options in the residential and transport sectors are then considered. Finally, the impacts on GHG emissions and total energy system costs are estimated.

The contributions of this study are thus twofold:

- Demand-side flexibility from smart controlled appliances and passenger EVs are incorporated in the TIMES framework to determine the optimal scheduling operation.
- The influence of demand-side flexibility of smart controlled appliances and passenger EVs on the whole energy systems is assessed.

We structure the paper as follows; Section 2 provides a review of the relevant literature on how demand-side flexibility has been modelled previously, and the insights provided. Section 3 describes the UKTM model, and the new approach to modelling demand-side flexibility. Section 4 presents the results of the analyses that shows the impacts of introducing demand-side flexibility for smart appliances and passenger EVs into the model. Finally, Section 5 draws out the main conclusions from the study.

2. Literature review

DSR is a means of reducing peak loads to avoid the procurement of extra electricity from conventional power plants and the resulting increased cost of electricity generation. However, in recent year, the concept of DSR has been expanded also to enable the matching of demand load profiles to electricity generation profiles as increasing intermittent renewable energy flows into the electricity grid. Some regulatory examples include reducing or interrupting consumption temporarily, shifting consumption to other time periods, and temporarily utilising onsite standalone generation [14].

DSR can participate in the wholesale markets in two ways [15]: price-based and incentive-based DR schemes. In a price-based scheme, consumers are offered time-varying rates for different time periods. Some example schemes include time of use (ToU), critical-peak price (CPP) and real-time price (RTP). In incentive-based schemes, consumers are encouraged to reduce their energy consumption upon request or according to a contractual agreement between the consumer and the utility company. Utility companies can be granted a certain level of authority to schedule or reduce energy consumption to save electricity generation costs. Interruptible tariffs, demand-bidding programs and direct-load controls (DLCs) all belong to this type of scheme. Almost all DSR programs require consumers' active participation and can cause disruption to daily routines, and therefore the impact of such measures on consumer behaviour is highly uncertain [16]. Therefore, this study only considers the DLC type of scheme as this minimises the interruptions to consumers and requires only passive compliance from consumers.

There have been numerous studies assessing the impact of demand-side flexibility via DSR on energy systems. Some of the recent studies have been reviewed here to identify the research gap, and are categorised into national-scale, sub-national-scale and whole energy systems model-related studies. Studies using whole energy system models are limited and directly relate to this study; therefore, they are reviewed separately.

2.1. National-scale studies

A range of studies has analysed the benefits of demand-side flexibility at a national scale. Fehrenbach et al. [17] used a TIMES-Heat-Power model to estimate the potential of flexible heating systems in Germany, including HPs and micro-CHPs, under varying conditions including fuel prices, CO_2 prices, VRE expansions and investments. In their study, focusing only on the residential heating and power sectors, they found that high fuel prices and a high share of VRE would favour heat pumps and insulation measures. Drysdale et al. [18] estimated the potential of load shifting from smart appliances, such as refrigerators, washing machines, and space and water heaters, in the future UK power system in 2030. Using energy projections of future loads fixed over time, they estimated the flexible domestic demand could be up to 59 TWh by 2030.

Nistor et al. [19] estimated the potential of flexible domestic appliances to provide operating reserve to the UK energy system for wind forecast error or unexpected shutdown of power plants. The shifting of smart appliances, such as washing machines, dish washers and tumble dryers, were simulated for households only to determine the potential in a typical day. They found that demand-side flexibility can provide up to 54% of the operating reserve requirements of the GB power system. Stötzer et al. [20] developed a heuristic optimisation procedure to estimate the maximum shiftable potential to adapt loads to VRE in the German power system in 2030 by shifting the load from domestic smart appliances, including refrigerators, washing machines, HPs, and air conditioners. The developments of domestic appliances and loads in other sectors were based on exogenous assumptions from other studies. Teng et al. [21] estimated the benefits of flexibility from HPs and EVs in the electricity sector in the UK in 2030 and 2050 with a detailed electricity system model, based on predefined technology penetration rates. They found that smart EVs/HPs can significantly enhance both the carbon savings and renewable energy integration benefits. Gils [22] used a detailed electricity system model, REMix, to determine the benefits of flexible loads from dispatchable end-use technologies, including heating and cooling systems, washing machines and industrial processes, for a future energy system with 70% of VRE in Germany. End-use sectors were not explicitly modelled but rather maximum potentials of DSR technologies were exogenously imposed. They found that about 5 GW of power plant capacity can be substituted while decreasing the utilisation of pumped storage hydro stations. Olkkonen et al. [23] estimated the hourly flexible demand potential from heating systems and then determined the impact on the Finnish power sector with a high share of VRE, the system costs and CO_2 emissions in 2030. The analysis found that DSR can integrate VRE efficiently, resulting in lower power system costs. Aryandoust and Lilliestam [24] investigated the maximum potentials of shiftable loads in the residential, commercial and industrial sectors in the future Germany energy system with 100% of electricity generation from VRE in a typical year. The potentials of flexible loads and the electricity supply capacity were determined independently. They found that DSR is suited for short-term services, such as spinning reserve, but its potential is low for longer-term services, such as secondary control. Strbac et al. [7], using WeSIM, a detailed electricity system investment model, estimated the benefits of incorporating flexible options into the UK electricity system in 2050 to reduce the investment in new power plant capacity and the integration costs of VRE. In the study, smart appliances, such as washing machines, dish washers, tumble dryers, EVs, HPs and a partial representation of industrial and commercial demand were considered flexible and suitable for DSR. However, the potential of the flexible loads was based on other research and exogenously fixed in the modelling framework. The study found that DSR can efficiently balance generation and demand in a future UK electricity system with a high share of VRE. A similar framework was also adopted in Sanders et al. [8] to further explore the impact of uncertainties relating to demand, cost of storage, cost of DSR and interconnection on the benefits of deployment of flexible technologies. They found that the UK could save 17–40 billion GBP across the electricity system from now to 2050 by deploying flexibility options.

2.2. Sub-national-scale studies

Other research has focused on sub-national areas, such as urban areas, islands, individual smart grids, and even small numbers of households. For example, Mahbub et al. [25] combined EnergyPLAN with a multi-objective evolutionary algorithm to determine Pareto-optimal configurations of power technologies, accounting for competing objectives of cost and GHG minimisation in a single year for a Danish city. For a set of pre-defined demands, several heating systems, such as HPs, were considered as dispatchable. Neves et al. [26] determined the benefits of flexible heating systems for a small island energy system, using three models, including HOMER, EnergyPLAN, and a self-built operation scheduling model. However, only the power sector was modelled in detail for a typical day while no clear GHG targets were imposed. They estimated that a 0.3% decrease in the operation costs can be achieved by an optimised generation dispatch strategy.

Jaramillo and Weidlich [27] determined the optimal scheduling of loads for hydrogen production and the charging of EVs in a smart grid in Germany. Using a multi-objective mixed integer linear programming model to reduce peak load, they found that energy storage is useful to trim the peak of electricity drawn from the public grid and DSR can keep the peak load at its possible minimum level. Soares et al. [28] proposed a multi-objective framework to determine the optimal day-ahead scheduling of energy resources for a smart grid in Portugal. A fixed potential for the load reduction program and EV deployment were considered in the framework. Ayón et al. [29] determined the optimal day-ahead load scheduling for flexible appliances in several residential and commercial buildings in a small region in Spain to reduce electricity bills while ensuring occupants' comfort. Washing machines, heating and cooling appliances and lighting were taken into account. Nan et al. [30] determined the optimal scheduling of various types of loads for a community connecting to a smart grid in China. Loads for lighting, cooling, cooking, and washing were included. The optimal scheduling reduces consumers' electricity bills, decrease the peak load and peak-valley difference, without causing discomfort to the consumers. Erdinc [31] determined the optimal operation of distributed generation technologies, storage technologies, EVs and shiftable appliances for smart households in a typical day with a mixed-integer linear programming model. They found that daily energy costs can be reduced by 35% compared to a base case with lower flexibility.

2.3. Whole energy systems model-related studies

There are only a very small number of studies estimating the benefits of flexible loads in whole energy systems and which reflect the dynamics across and between sectors. As we have argued, energy system models (ESMs) provide a framework for an integrated approach across sectors for long-term analysis, and therefore have the potential to bring new insights. In addition, the absence of flexibility in ESMs means a key option to transition to a low carbon system is missing. A small number of studies have been undertaken but either at a sub-national scale in the medium-term or for a given year. Pina et al. [32] determined the impacts of flexible loads in the residential sector on the penetration of VRE on a small island in Portugal using a TIMES model. However, the study only modelled the development up to 2020 and no clear GHG targets were imposed. They found that, with DSR, investments in new generation capacity can be significantly delayed while improving the operation of the existing capacity. Pina et al. [33] further evaluated the effects of flexible charging loads of EVs to accommodate a higher share of VRE on the same island. A TIMES model was linked with a short-term electricity model to test the feasibility of the projected technology mix. However, flexible loads in the residential sector and GHG targets were not considered. The study found that flexible charging strategy can double the share of VRE, and consequently reduce GHG emissions by 0.3–1.7%. Kwon and Østergaard [34] assessed the potential of flexible demand in residential, commercial and industrial sectors in the 2050 Danish energy system with EnergyPLAN. Refrigerators, washing machines, ventilation systems, space heaters, pumping systems were taken into account. However, the capacities of the supply and demand technologies were exogenous, taken from an official projection. They found that the potential of flexible demand is about 7% of the electricity demand, which has limited benefits to the energy system.

According to authors' best knowledge, Krakowski et al. [13] is the only study which has incorporated flexibility measures into a long-term whole energy systems model to determine the feasibility of various penetration rates of VRE, ranging from 40% to 100%, in the French power system out to 2050. Nonetheless, the DSR potentials were based on expert assumptions rather than by estimation of the penetration of individual smart appliances. Furthermore, the study mostly analysed the influences on the power sector without addressing the dynamics across all sectors. They concluded that significant investments in dispatchable power plants, electricity imports and DSR are essential to accommodate high shares of VRE.

According to the literature review, national-scale and subnational-scale studies typically only investigate the influences of DSR on few specific sectors and adopt fixed projections of future energy demand, without considering the interactions across sectors in an energy system. While a few whole energy systems model-related studies have tried to reflect the interactions between sectors, those studies still estimate the potential of demand-side flexibility based on official projections or experts' assumptions rather than incorporating flexibility options endogenously. Therefore, modelling of the benefits of demand-side flexibility have not been effectively captured in ESMs in the previous studies. This study thus develops a framework to model demand-side flexibility in an ESM to bring the following strengths: a longer-term energy planning horizon at the national scale, the impacts of flexibility in one part of the system on other parts, and the inter-temporal impacts over a multi-year time horizon.

3. Methodology

3.1. Current representation of demand-side flexibility in UKTM

UKTM was adopted in this study to assess the role of DSR in the residential and transport sectors of the wider UK energy system. The model is based on the model generator TIMES (The Integrated MARKAL-EFOM System) [35], which has been developed and is maintained by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency.

UKTM is a bottom-up, technology-rich, dynamic, linear programming optimisation model consisting of numerous alternative energy supply/end-use technologies and describing the whole UK energy system [36]. The model is comprised of eight supply-side and demand-side sectors, including resource mining and imports, fuel refineries, electricity generation, transport, industrial, residential, service, and agricultural sectors. All sectors are calibrated to the base year of 2010, using official energy statistics [37], including energy supply and consumption, and the existing stock of technologies. In UKTM, a large variety of future supply and demand technologies are represented by techno-economic parameters such as capacity factor, energy efficiency, economic lifetime, capital costs, O&M costs, etc. In addition to all energy flows, emissions of CO_2, CH_4, N_2O and HFC from energy use are also accounted for. The simplified structure of the model, known as the reference energy system, is illustrated in Fig. 2. For a more detailed description of the model, refer to Daly and Fais [36].

In UKTM, various end-use technologies, such as gas boilers, heat pumps and electric storage heaters, are chosen to satisfy energy service demands (ESDs), such as space heating, at the lowest cost while fulfilling the UK GHG emission reduction targets set in five carbon budgets and for 2050 [38]. Demands for energy services are added as exogenous inputs to the model, as is their diurnal time of use profile. Therefore, when electricity is used to meet an ESD, it also needs to match the temporal profile. The model is able to reduce consumption at a given point in time as costs increase, for example in the peak period, based on price elasticities of demand [35]. However, there is no existing mechanism in UKTM to maintain the same level of demand but to shift it to other periods, thereby modelling demand-flexibility. A novel approach to incorporate this flexibility in UKTM has thus been developed and is described in Section 3.4.

3.2. Temporal representation in UKTM

Due to the complicated structure of the model, a more aggregated temporal resolution is used to represent the variability of energy supply and demand to avoid excessive solution times [17]. UKTM uses 16 time-slices (four diurnal times-slices in four seasons) to represent the temporal variations of energy supply and consumption technologies based on empirical evidence [39]. The definitions of these time-slices are shown in Table 1. The temporal representation, which has intra-day time-slices longer than 1 h, is a characteristic of long-medium term energy optimisation models (20–50 years) [40,41].

The supply and use of electricity in the model, therefore, conforms to this temporal structure. This means that historical data used to calibrate specific technologies, such as intermittent renewables, typically needs to be aggregated. For example, the hourly capacity factors of wind power in each season are based on Sinden [42] which took into account 34 years of wind speed data. The capacity factors are higher in the winter and lower in the summer. Irrespective of the season, the capacity factor usually peaks in the day time-slices, between 7:00 and 17:00, and gradually reduces until night time-slices, when the capacity factors remain relatively stable until the next morning. Temporal variations of solar PV capacity factors are also derived from historical data over an 8-year period. Capacity factors in the day time-slice reach the highest level in summer and drop to the lowest in winter. Except in the summer, capacity factors in the peak time-slices are close to zero.

In the end-use sectors, the demand profiles are also derived from relevant reports and studies [21,43,44]. For example, the charging profile of passenger EVs is based on the trial results conducted in Low Carbon London [21,44]. The average charging demand usually gradually increases from the lowest level in the day time-slice until the evening time-slice when the demand reaches its highest level. Then, charging demand begins to decrease during the night time-slice. Conversely, because of the higher annual driving distance per vehicle of the light-duty vehicles (LDVs), heavy-duty vehicles (HDVs) and buses [45], those types of EVs are assumed to be charged during the night time-slices only. Space heating demand is based on Summerfield et al. [43]. Peak heating demand occurs in the peak time-slices as residents arrive home from work. The profiles of ESDs for lighting, washing clothes, refrigerating, etc. are set as the electricity consumption patterns of appliances reported in BEIS [9].

3.3. Challenges of modelling demand-side flexibility in UKTM

In UKTM, various modelling structures have been implemented to represent the UK energy system in a sensible way. Some examples are shown in Fig. 3. In the simplest case, an end-use technology might deliver energy services directly to fulfil demands, such as light-emitting diodes (LEDs), which provide lighting to households without any intermediate technology. However, some energy services provided by end-use technologies need to be delivered to households to fulfil demand requirements, such as heat generated from gas boilers and then

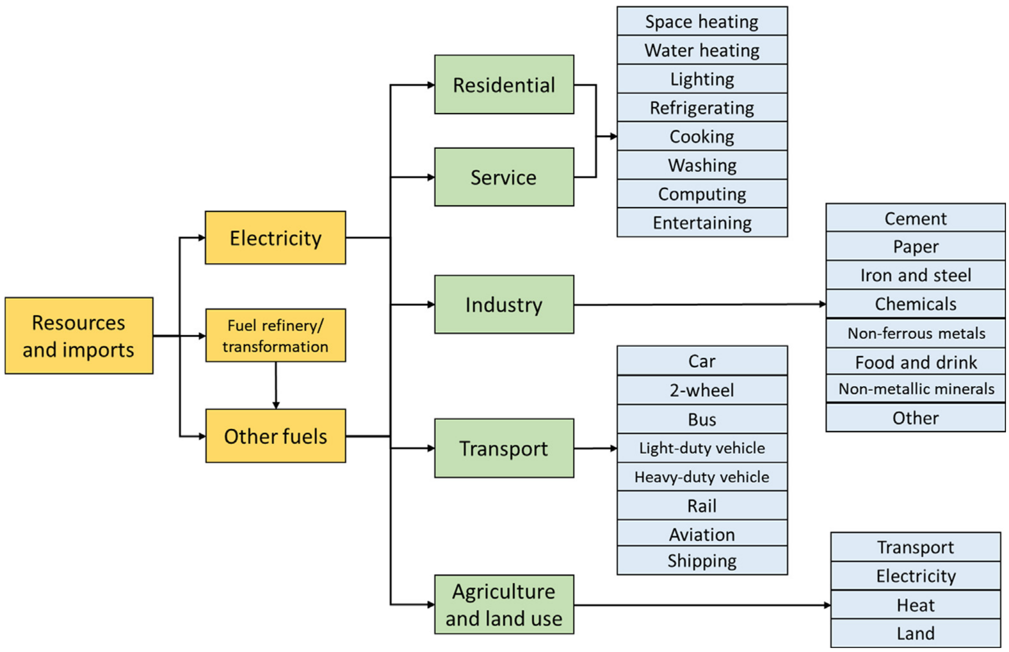

Fig. 2. Schematic of the simplified reference energy system of UKTM.

Table 1
Temporal representation in UKTM.

Season	Intra-day period	Time represented	Notes
Spring (P)	Night (N)	00:00–07:00	Lowest demand
Summer (S)	Day (D)	07:00–17:00	Includes morning peak
Autumn (A)	Evening peak (P)	17:00–20:00	Peak demand
Winter (W)	Late evening (E)	20:00–00:00	Intermediate

transmitted to households via radiators or underfloor piping systems. Finally, end-use technologies might comprise storage systems so that the energy consumption profile can be different from the service provision pattern. For instance, EVs can be charged during the night or anytime when the EVs are parked for a period of time. Two technologies, a storage and end-use device, are bound together to represent this technology type, such as an EV. The charging profile of EVs is regulated by the battery technology, which stores the electricity in a given period before it is used in the drivetrain to provide mobility services in another time period.

These various modelling structures impose serious challenges for modelling demand-side flexibility via DSR in the model. The challenge is that temporally-resolved energy demands are expressed as ESDs such as heating, cooling, and hot water, which in turn influence the operation of the technologies providing these energy services. For example, space heating can be met by both a gas boiler and an electric appliance. The challenge is to ensure shifting at the technology level for the electric appliance, which in turn influences the shape of the demand profile across different ESDs.

As currently configured, except in the simplest case (of LED lighting), the model cannot just shift ESDs from one time-slice to another to represent load-shifting for smart appliances.

3.4. Enhancing representation of demand-side flexibility in UKTM

To tackle the challenge of modelling DSR, a novel approach has been proposed and implemented in UKTM. The following equations were introduced into the existing TIMES model to regulate DSR of smart appliances and EVs. The definition of the variables is presented in Table 2. This approach can be applied to any shiftable technology wherever their DSR characteristics, such as maximum shiftable rate, can be estimated.

$$VarAct_{t,i,s} \leqslant C2A_i \times AF_{t,i,s} \times VarCap_{t,i} - VarRdc_{t,i,s} + \sum_{sl \neq s} VarSht_{t,i,sl,s} \tag{1}$$

$$VarRdc_{t,i,s} = \sum_{sl=1}^{SN} VarSht_{t,i,s,sl} \tag{2}$$

$$VarRdc_{t,i,s} \leqslant MXSR_{t,i,s} \times C2A_i \times AF_{t,i,s} \times VarCap_{t,i} \tag{3}$$

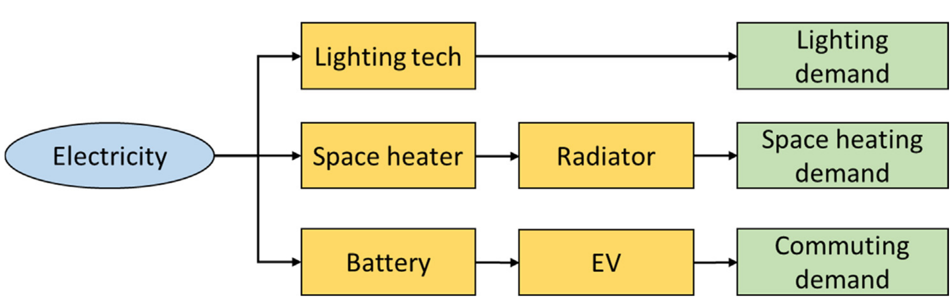

Fig. 3. Example modelling structures linking smart appliances with demands.

Table 2
The definition of variables.

Variable	Definition
i	Technology index
s, sl	Time-slice
t	Year
dm	Demand type
SN	Total number of time-slices in a year
NDM	Total number of smart appliances contributing to provide service for a specific demand
$VarAct_{t,i,s}$	Activity of technology i in time-slice s in year t.
$VarCap_{t,i}$	Capacity of technology i in time-slice s in year t.
$C2A_i$	Coefficient to convert capacity to the activity which can be generated by technology i.
$AF_{t,i,s}$	Available ratio of total capacity of technology i can be used in time-slice s in year t.
$VarRdc_{t,i,s}$	Reduced activity of technology i in time-slice s in year t.
$VarSht_{t,i,sl,s}$	Shifted activity of technology i from time-slice sl to s in year t.
$MXSR_{t,i,s}$	Maximum shiftable rate of activity of technology i in time-slice s in year t.
$VarDM_{t,dm,s}$	Energy service demand dm after shifted in time-slice s in year t.
$DM_{t,dm,s}$	Original energy service demand dm in time-slice s in year t.
$DEFF_{i,dm}$	Delivery efficiency from technology i to demand dm.

$$VarDM_{t,dm,s} = DM_{t,dm,s} - \sum_{i=1}^{N} DEFF_{i,dm} \times VarRdc_{t,i,s} + \sum_{i=1}^{NDM} DEFF_{i,dm} \times VarSht_{t,i,sl,s} \ (i \text{ is not storage tech.}) \quad (4)$$

Eq. (1) determines the final load of a smart appliance or EV i according to its existing capacity in year t, together with the reduced load and the load shifted from other time-slices to the time-slice under consideration. The reduced load is then shifted to other time-slices, as regulated in Eq. (2). The load can only be shifted to feasible time-slices in a typical day, i.e. within 24 h. For example, operations of refrigerator compressors might be shifted to the day time-slices from the peak-load time-slices. Furthermore, the maximum shiftable load of the technology is limited by Eq. (3), where $MXSR_{t,i,s}$ is the physical potential of load shifting for the technology. Finally, the temporal pattern of ESDs should be adjusted accordingly since the time-of-use of those shiftable appliances has changed. Eq. (4) is thus applied to ensure the aggregate shifting of technologies is equal to the shifting of ESDs. It is worth noting that there might be more than one technology which can contribute to a specific ESD and is shiftable. Therefore, the load shifting of all those technologies should be included. Furthermore, a delivery coefficient, $DEFF_{i,dm}$, is adopted to reflect the efficiency loss during the delivery process via radiators. However, technologies with storage systems, such as EVs and electric night storage heaters, do not contribute to the shifting of ESDs as the usage patterns are independent of charging profiles.

The maximum shiftable rate of technology activity, $MXSR_{t,i,s}$, takes into account both the shiftable potential and penetration rate of smart technologies. For example, in theory, the charging load of EV can be fully shifted. However, this study conservatively assumes that there is still no significant deployment of smart controls by 2020, given the current status of the infrastructure and regulatory framework. As a result, no charging load can be shifted in 2020.

This is demonstrated in Fig. 4. On a typical day an ESD, such as space heating, is supplied by two technologies a and b. The temporal profile of the ESD is simply the aggregation of the demand profiles of the two technologies if there is no energy lost in delivery. The proposed equations are imposed to ensure the demand reduction of a technology in a time-slice is equal to the shifted demand to the other time-slice. This is shown where the demand provided by technology a in the peak time-slice *VarRdc(a,peak)* is reduced, shaded in green,[1] and shifted to the day time-slice *VarSht(b,peak,day)*, shaded yellow. The final ESD profile is thus determined by the demand reductions and shiftings of individual technologies. As shown in Fig. 4, the final ESD of c in the daytime time-slice *VarDM(c,day)* is equal to the original ESD *DM(c,day)* plus the shifted demands of two technologies, *VarSht(a,peak,day)* and *VarSht(b,night,day)*. The ESDs in the night and peak time-slices are reduced accordingly as the demands of technologies a and b have been reduced in the peak and night time-slices respectively.

However, it is worth noting that the proposed approach only enables the demand reduction and shifting across time-slices in a typical day. The optimal DSR operation scheduling is still determined by the original objective function of UKTM to minimise the total energy system costs, including electricity generation costs and other energy-related costs.

3.5. Parameterising demand-side flexibility in UKTM

Residential appliances and passenger EVs are used as examples in this analysis to represent the demand-side flexibility from end-use sectors. However, not every appliance can be easily controlled via smart systems without inconveniencing consumers. There are some appliances for example that consumers may always need access to, for example, lighting and cooking during the evening, and behaviour change may be unrealistic or very difficult to affect [34]. Therefore, the flexibility of these appliances is not considered in this study.

A range of flexible end-use technologies was identified for use in the DSR modelling (Table 3), such as washing machines and tumble dryers which can be more readily shifted with a smart control system to those time-slices where electricity prices are lower, compared to others with much lower shiftable potentials and smart penetration rates. Consumer acceptance is assumed to be higher in such cases where activities, such as clothes washing, are less time-dependent [18]. The other type of flexible end-use technologies which can be shifted are those with storage capability. For example, EVs can be charged in any time-slice once parked up for a period of time and connected to the electricity grid. However, even though electric LDVs, HDVs and buses also have storage capability, the charging profiles of those technologies are assumed to be inflexible due to their long driving range. As for space heaters, heat generated can usually be retained in the house for a period of time, allowing for the operation of space heaters to be shifted [46]. The same assumption is applied to water heaters and refrigerators [47]. Based on previous studies [46–48], electricity loads of those appliances can be shifted by up to one hour without obvious disruption to consumers.

The EU Smart-A project investigated how smart domestic appliances can contribute to load management in future energy systems in the EU [49]. This project carried out surveys in five countries, including the UK, to understand consumers' acceptance of smart appliances which are regulated. The acceptance of smart appliances among UK respondents is consistently high across the different appliances. The acceptance rates of smart regulations on different appliances are estimated to be in the range of 92–98%. While respondents may overstate their acceptance, this still suggests that these appliances could have a potentially high uptake in the long term. However, the smart systems will be enabled by the necessary ICT infrastructure. The UK government aims to roll out smart meters, a crucial part of that infrastructure, to every household by 2020; as of 2017, there were 8.6 million meters operating across Great Britain [50]. It is hoped that this will enable a smarter electricity market to provide flexibility to both the supplier and consumers [11]. With this roll-out to scale by 2020, it is assumed that by 2050, there would be the potential for smart appliances to be installed in every household.

The assumed shiftable potential and penetration level of smart

[1] For interpretation of color in Fig. 4, the reader is referred to the web version of this article.

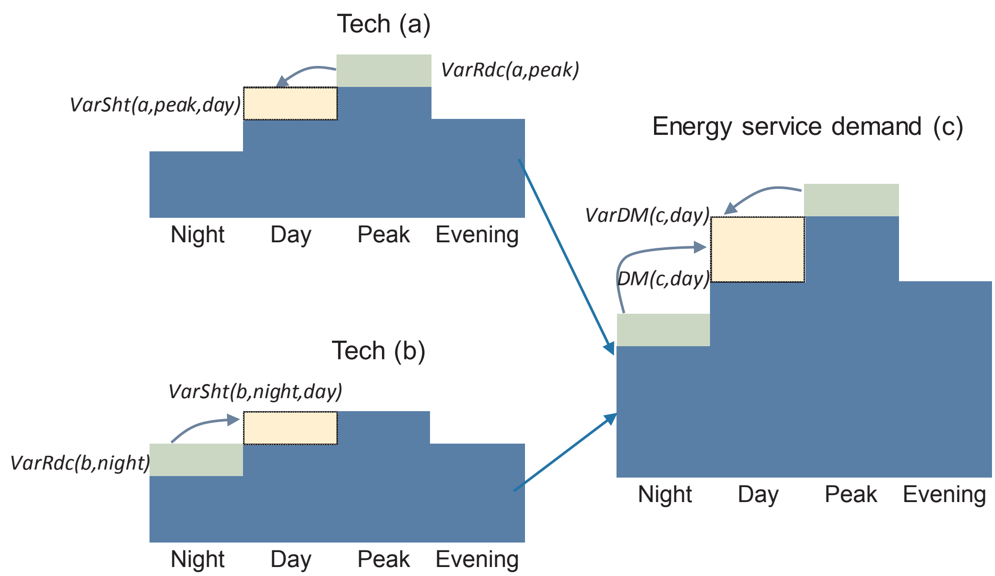

Fig. 4. An illustration of how energy service demand is shifted across the diurnal profile.

Table 3
Shiftable potentials and smart penetration rate of smart appliances and electric vehicle.

Technology	Shifting mechanism	Shiftable potential	Smart penetration rate in 2020	Smart penetration rate in 2050
Lighting	Consumer behaviour	0%	0%	0%
Oven/Stove	Consumer behaviour	0%	0%	0%
TV/Computer	Consumer behaviour	0%	0%	0%
Washing machine	Central control	100%	0%	100%
Tumble dryer	Central control	100%	0%	100%
Water heater	Central control	1 h	0%	100%
Space heater*	Central control	1 h	0%	100%
Refrigerator/Freezer	Central control	1 h	0%	100%
Electric vehicle**	Central control	100%	0%	100%

* Electric night storage heaters, heat pumps and district heating from electric heaters and heat pumps are included.
** Only passenger EVs are taken into account.

appliances are set out in Table 3. Shiftable potential indicates how much of the electricity consumption of a technology can be shifted. While the smart penetration rate is the percentage of technologies that can be controlled remotely by utility companies. A zero value for shiftable potential and smart penetration rates means those technologies are not considered in the proposed modelling framework.

Other supply-side flexibility measures are also included in UKTM, such as pumped hydro and various battery technologies (e.g. compressed air storage and lithium-ion battery).

3.6. Scenarios

Two scenarios without and with DSR, LGHG_Ref and LGHG_DSR, were modelled to investigate the impacts of demand-side flexibility on long-term energy transition pathways. The GHG targets are the same for both scenarios; the legally binding 2050 target to reduce GHG emissions by 80% relative to 1990 levels and the five UK carbon budgets, including a 57% reduction by 2030 [38]. The GHG targets for those years between 2030 and 2050 are simply the interpolation of the targets in those two years. Moreover, in both cases, the recently proposed ban on sales of new diesel and petrol cars and vans from 2040 to tackle air pollution are also taken into consideration [51]. The key distinction between the scenarios is that LGHG_DSR allows for the DSR potential of smart appliances and passenger EVs in the residential and transport sectors, while LGHG_Ref does not. In the latter, the usage patterns of residential appliances are fixed and cannot be shifted to other time-slices while the charging profile of passenger EVs is also fixed based on drivers' routine charging behaviour [21]. The optimal scheduling of the smart appliances and EVs were then revealed by comparing the differences between these two cases.

4. Results and discussion

4.1. System-wide electricity supply and consumption

The hourly electricity supply by generation type for the two cases are illustrated in Figs. 5 and 6. CHP is listed separately as it is deployed in the end-use sectors using various fuels, such as oil, gas and biomass. The profiles of electricity consumption are the same as those for electricity supply, and therefore not presented here. Figs. 7 and 8 present the differences of electricity supply and consumption between the two cases respectively, in which the positive values indicate that more electricity supply is generated by a specific fuel type in the case with DSR; negative values imply the opposite. Since UKTM only determines electricity supply and consumption in time-slices longer than an hour, the results were post-processed into hourly-resolved figures for further analysis. To do this, the electricity supply and consumption in each time-slice were divided by the total number of hours in the time-slice.

As shown in Fig. 5, the reference case with no DSR (LGHG_Ref), the power sector is gradually decarbonised by replacing fossil fuel plants with low-carbon capacities, such as wind turbines, nuclear and biomass-fuelled power plants with CCS. Unabated coal-fired power plants are fully phased-out by 2030 due to the target set by the UK government [52].

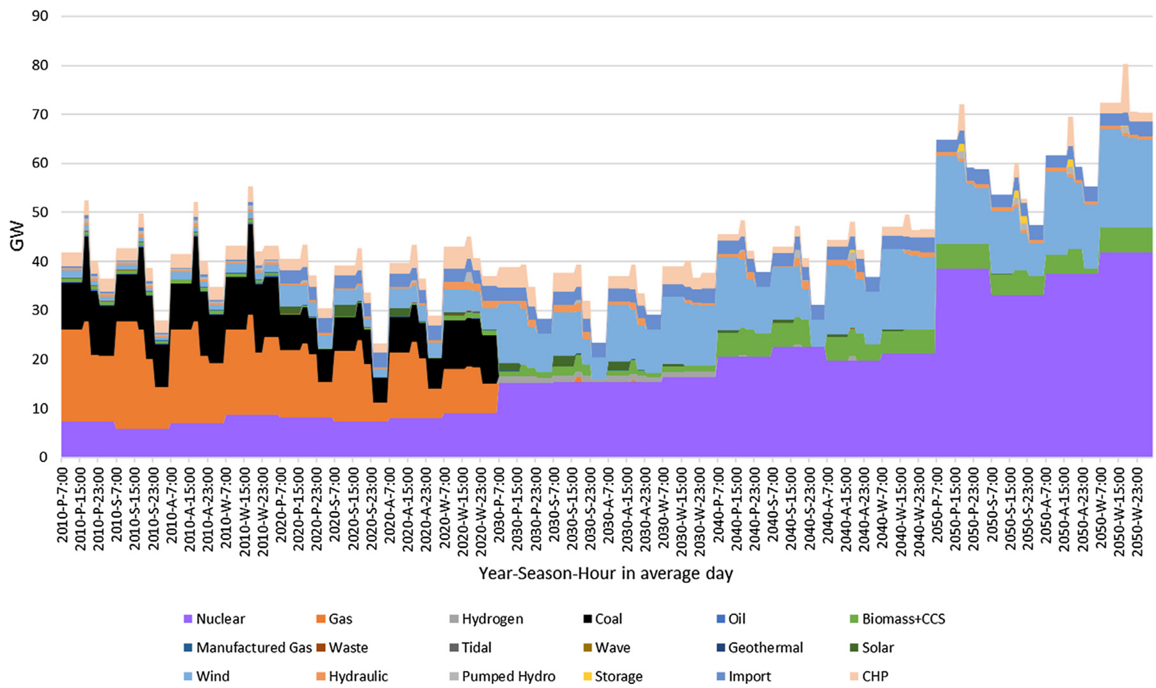

Fig. 5. Hourly electricity generation by fuel for the case without DSR (LGHG_Ref).

As the total electricity supply increases, due to growing electrification of the end-use sectors, the peak load also rises significantly, reaching a high point of 80 GW by 2050. At the same time, the gap between peak and average load widens to as much as 10 GW. Sufficient back-up power capacity, such as dispatchable CHP, is thus required to provide extra electricity to meet the increase of electricity demand in the peak load period.

In the case with DSR (LGHG_DSR, Fig. 6), prior to 2040, the peak loads are still much higher than the average load, with low adoption rates of smart appliances and EVs. The peak loads then gradually disappear as the demand from increased smart appliances and EVs are shifted to reduce the peak load. Consequently, the average loads in other time-slices increase so that the electricity supply profile in 2050 becomes much smoother across all seasons.

The differences in the electricity generation mix between the two cases (with and without DSR) are illustrated in Fig. 7. From 2030, the LGHG_DSR case sees increased generation from nuclear power plants to further reduce GHG emissions and electricity generation costs, without too much back-up operation of other dispatchable power plants. This is possible due to the increasing level of DSR which smoothens the profile of electricity consumption. However, this pattern changes in 2050. At this point, much more wind power can be introduced to fulfil the increase in demand under the LGHG_DSR case, as the load flexibility from smart appliances and EVs is sufficiently high to allow for a higher

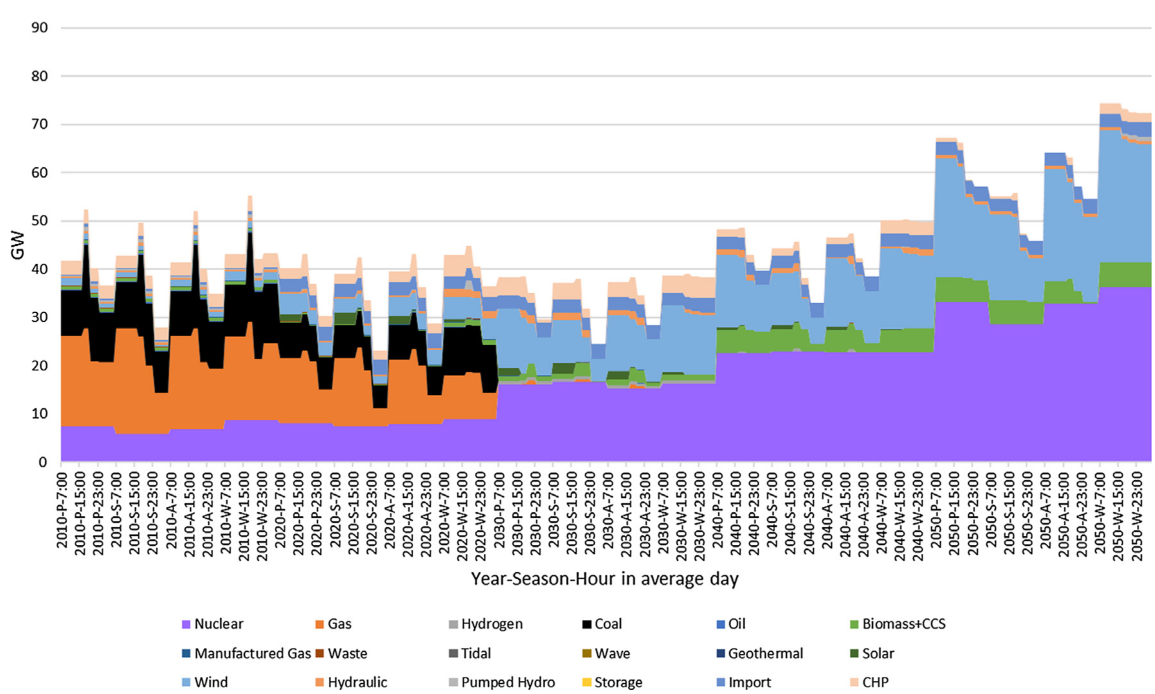

Fig. 6. Hourly electricity generation by fuel for the case with DSR (LGHG_DSR).

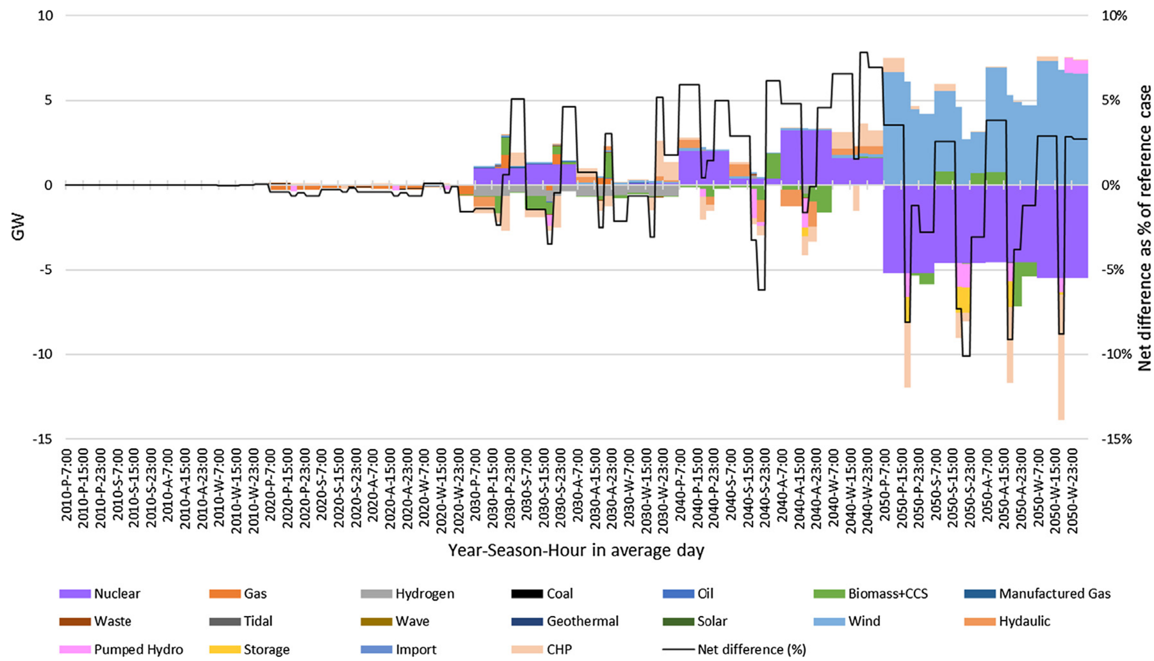

Fig. 7. Differences of hourly electricity generation by fuel between cases with and without DSR (LGHG_DSR – LGHG_Ref).

adjustment of its profile (through shifting) to match with the fluctuation of wind power. In earlier periods, where smart appliance and EV deployment is lower, a large increase of VRE would likely require additional higher cost storage systems to balance the system; as a result, the higher adoption of VRE at that point in time would not be a cost-effective choice to meet electricity demand.

Other power technologies also play a crucial role in balancing the energy system, including CHPs, pump hydro, storage systems and biomass-fired power plants, but this reduces with the increase role of DSR. Less dispatchable generation from CHPs is needed during peak load hours, while lower levels of pumped hydro and battery storage systems are required. With the flexibility from DSR, investments of around 1.5 GW of storage systems can be avoided, saving up to 120 million GBP cumulatively. Crucially, existing pumped hydros do still provide stored electricity during the night time-slice in 2050 to meet increased demand, while the operation of biomass power plants with CCS is adjusted to supply more electricity in daytime hours.

Overall, the net difference between the two cases varies by between 8% and −10% of the total electricity supply in the reference case. The difference increases with increasing deployment of smart appliances and EVs. While the electricity supplied in the peak period is reduced by around 9% (7 GW) in 2050, supply in other hours increases in the range of 3–6%. As for the net differences before 2020, these occur due to lower adoption of electric appliances in the LGHG_DSR case compared to those in the reference case, rather than as a result of demand-side flexibility.

A similar pattern of net difference in sectoral electricity consumption to that for electricity supply is shown in Fig. 8. Differences between the patterns in Figs. 7 and 8 are due to the shifted or reduced charging profile of pumped hydro and battery storage systems. For example, the

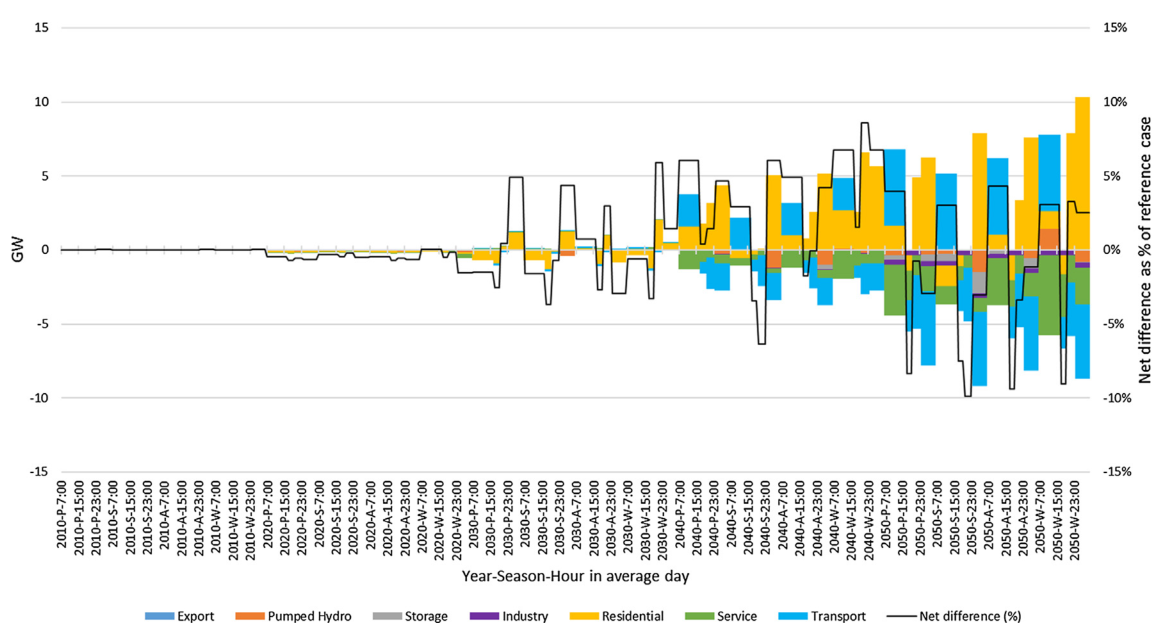

Fig. 8. Differences of hourly electricity consumption by sector between cases with and without DSR (LGHG_Ref – LGHG_DSR).

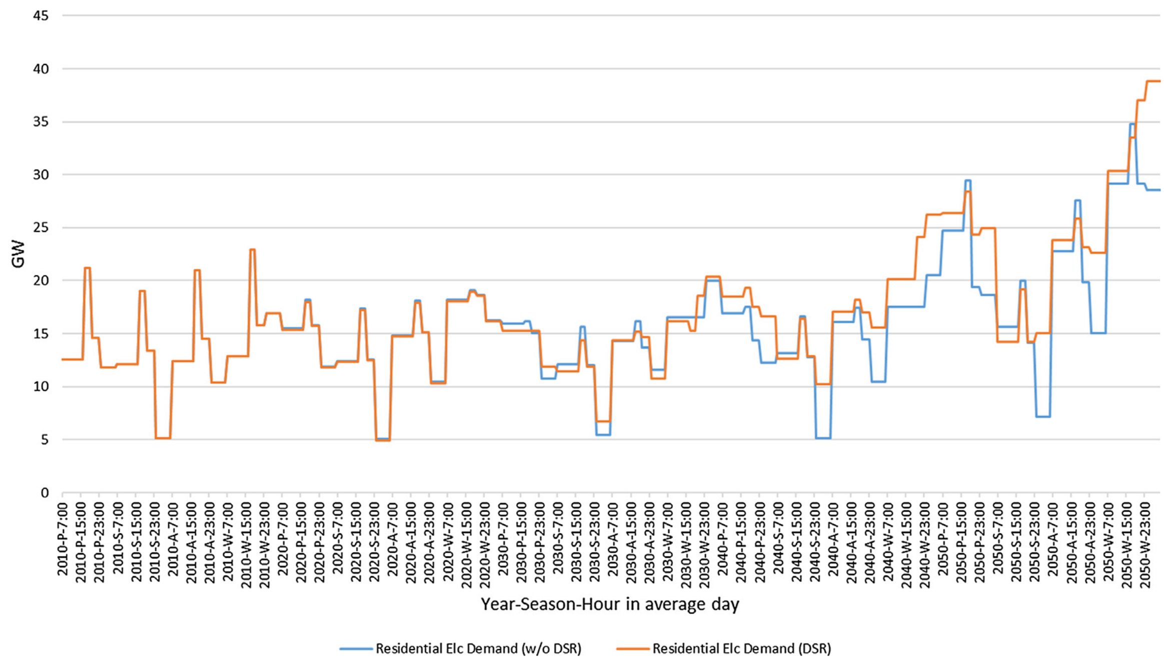

Fig. 9. Total electricity consumption in the residential sector in both scenarios.

net difference in total electricity consumption is 0.2% less than that of total electricity supply in the winter night hours in 2050. This is caused by the shifting of pumped hydro charging from the night time-slice to the daytime time-slice.

The differences in Fig. 8 stem from the load shifting in the residential and transport sectors as the model exploits the flexibility in these sectors to balance the system. However, marked variations can also be found in other sectors, such as the service and industrial sectors, highlighting that the flexibility of smart appliances and passenger EVs also influences the technology mix in end-use sectors across the energy system, to reduce the system costs. Less electricity is consumed in both service and industrial sectors to reduce the investments in electricity-using technologies that are not flexible in the model.

4.2. Electricity consumption in the residential sector

Under the reference case (Fig. 9, LGHG_Ref), the hourly peak load in the residential sector increases from about 23 GW in 2010 to about 35 GW in 2050 under a case of high electrification of heating and other appliances. However, as the demand patterns are fixed in the absence of smart control, the difference in peak loads and the other average loads widens over time, by up to 10 GW. The sharp increase in residential electricity consumption between time-slices is due to the increases in heating and cooking demand in the evening of a work day. The absence of heating demand in the summer night time-slices also leads to a dramatic drop in electricity consumption.

The LGHG_DSR case, on the other hand, exploits the shifting capabilities of smart appliances to reduce the significant differences in demand between time-slices. As a result, sharp peak loads in winter peak load hours are eliminated by 2050 and the deep troughs in summer night time-slices are also eased. Even though peak loads still appear in other seasons, the difference in load between time-slices reduces further, such as the gap between night and evening time-slices drops from 5.6 GW to 3.5 GW as the load in the evening time-slice rises. Higher loads in the LGHG_DSR case are observed after 2030 as much more electricity-using smart appliances are introduced into the system. After 2030, the increase primarily takes places in night time-slices. Approaching 2050, almost all loads across non-peak time-slices are much higher than those in the reference cases.

Fig. 10 shows the net difference in hourly electricity consumption between the two cases, and which demands are responsible. Increases relative to the reference case of about 11% in spring night hours in 2030 to 110% in summer night hours in 2050 can be observed. From 2040, more electric heaters and HPs are installed in households, with requisite increases in the electricity consumed. However, the peak loads of those heaters are not observed during the peak time-slice but have been shifted to other time-slices. In addition to shifted heating loads, washing machine loads are also shifted from peak and evening time-slices to night time-slices. These load shifts result in increases, such as those high net-positive differences in percentages, in the night time-slices. As for the extremely high net percentage differences, such as the more than 100% increase in summer night time-slices, this is because of the exceptionally low demand in those time-slices in the reference case.

4.3. Electricity consumption in the transport sector

As shown in Fig. 11, load shifting is also observed in the transport sector. In the reference case, electricity consumption by EVs increases dramatically from almost zero to about 16.1 GW during night time hours in 2050, with about 45 million passenger EVs and 6.9 million electric LDVs deployed by 2050. The charging profiles of EVs are more regular without seasonal variations. According to the survey [21], even though EVs are also charged in day and night time-slices, most drivers start to charge EVs once they arrive home. Other EVs, such as electric buses, LDVs and HDVs, only charge in the night time-slices, as assumed in the reference case. The shares of these EVs are thus an important determining factor on the final charging profile. In 2030, the passenger EVs are still fewer than other types of EVs, and therefore the peak demand occurs in the night time-slices. As passenger EVs are increasingly deployed from 2040, the peak demand then shifts to the evening time-slices, when the passenger EVs is more likely to be charged, such as the load at 2040-A-22:00. However, the sharp increase of electric LDVs in 2050, resulting from the ban on new ICE vehicles, further shifts the peak demand to the night time-slices.

In contrast, the charging profile of EVs is much smoother in case with DSR (LGHG_DSR), with the same number of passenger EVs, about 45 million, and fewer number of electric LDVs, about 6.3 million, deployed by 2050. From 2030, the loads in the night time-slices are shifted to the day time-slices to smoothen the load profile by changing the charging time of passenger EVs. From 2040, in addition to the loads

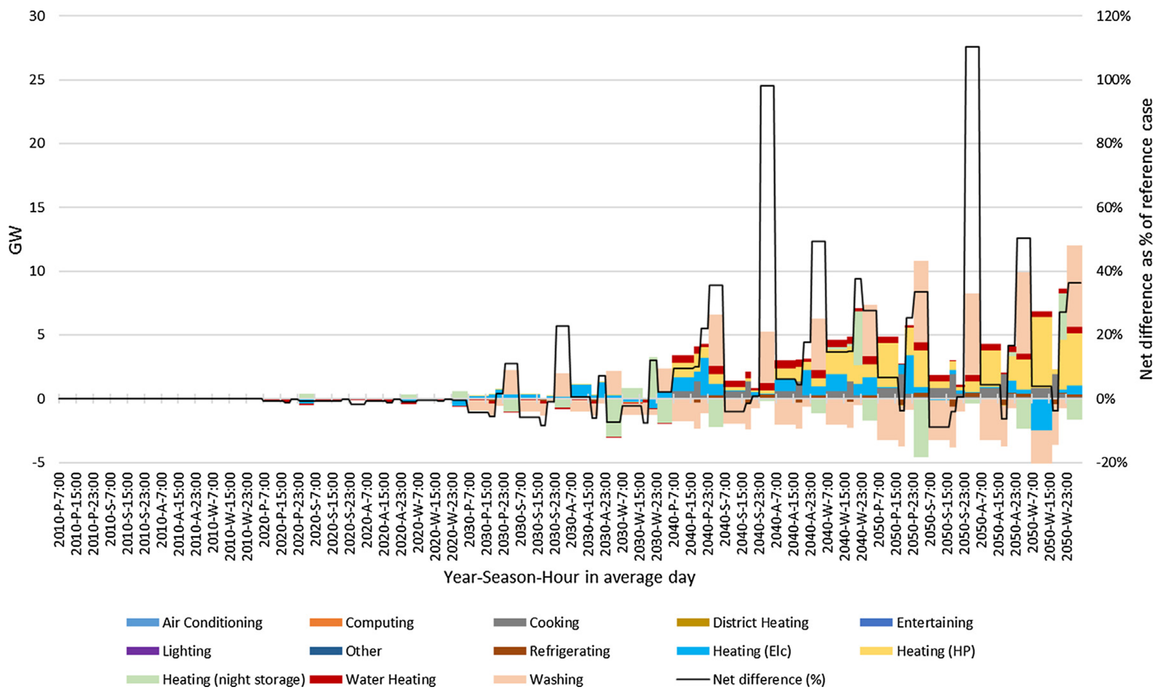

Fig. 10. Differences of hourly electricity consumption across demands in the residential sector between cases with and without DSR (LGHG_DSR – LGHG_Ref).

shifted in the night time-slices, those in peak time-slices are also shifted to offset the higher but less flexible demands in other sectors, such as those in the residential and service sectors. By 2050, the charging profile of EVs is relatively stable over all time-slices, except for the reductions in the peak time-slices.

The net differences fluctuate more frequently than in the residential sector, as shown in Fig. 12. In 2050, the increased charging loads in the day time-slices are as high as 88% while the reduced loads are 31% less in the night time-slices. Average loads in the peak, evening and night time-slices are shifted to the day time-slices to smoothen out the charging profile of EVs. Due to high yet inflexible demand in the night time-slices created by an increased number of electric LDVs (due to the ban on ICE vans sales after 2040), a share of electric LDVs is replaced by LPG-based LDVs to reduce the demand in the night time-slices. The inflexible demand of electric LDVs also determines how much flexible demand of passenger EVs should be shifted to manage the overall load.

4.4. Differences in fuel consumption

Overall, due to the greater flexibility of end-use technologies in the residential sector, increased electrification occurs to reduce GHG emissions. The load profile of electricity consumption can be shedded

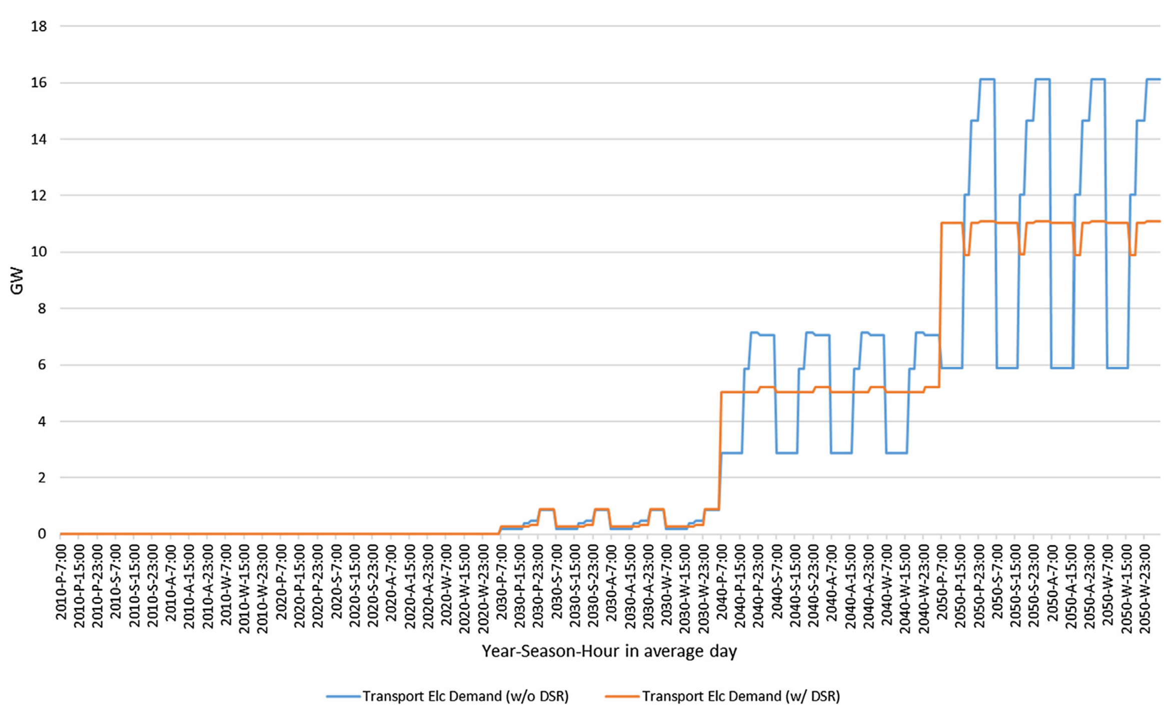

Fig. 11. Electricity consumption in the transport sector in both cases.

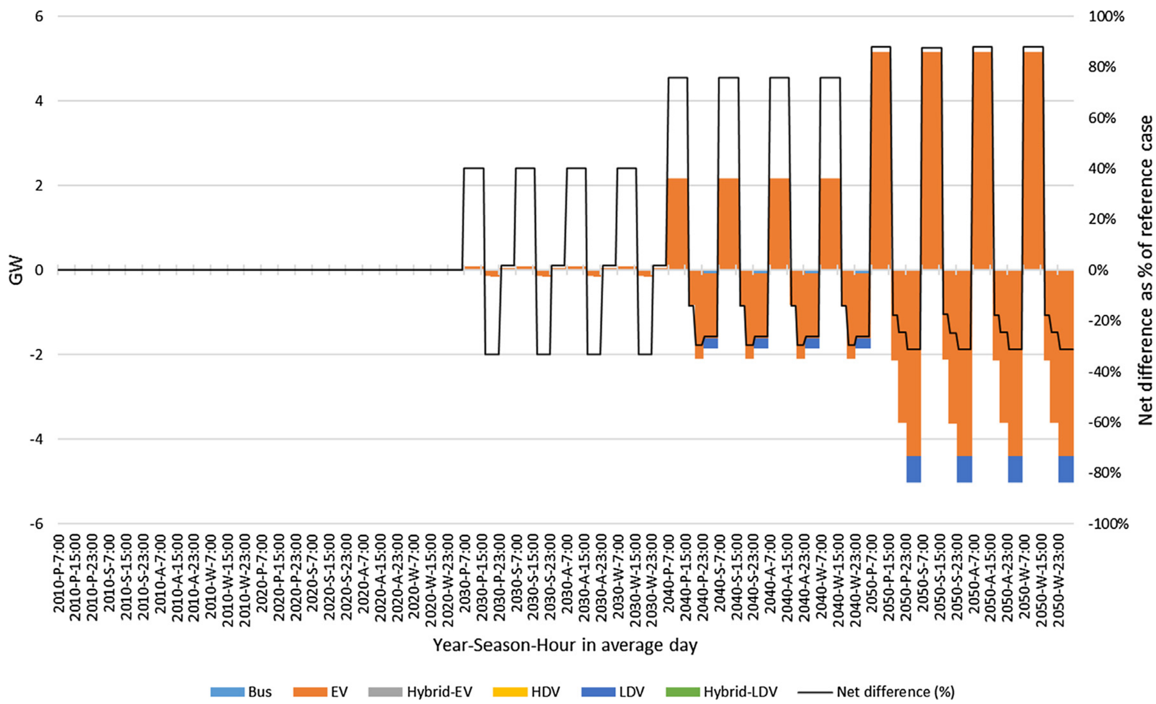

Fig. 12. Differences of hourly electricity consumption by vehicle type in the transport sector between cases with and without DSR (LGHG_DSR – LGHG_Ref).

and shifted via controlling smart appliances and passenger EVs to other time-slices to exploit more variable but cheaper wind power in 2050. More specifically, compared to the reference case, the LGHG_DSR case requires about 346 TWh more electricity for heating and cooking, displacing other fuels including 293 TWh of natural gas and 529 TWh of hydrogen. At the same time, a sharp increase of 71 TWh of LPG is consumed in the transport sector to reduce the demand for electricity consumption from electric LDVs. The fuel-switching also happens in other sectors as emissions savings in the residential sector allows more fossil fuels in other sectors. This includes higher consumption in the service sector for heating and cooking and in industrial processes, and at the same time reducing investments in electric end-use devices, such as heat pumps, where such appliances do not have DSR flexibility.

4.5. Differences in sectoral GHG emissions

The fuel-switching in sectors leads to variations in sectoral GHG emissions, as shown in Fig. 13, although the total GHG emissions in both cases are similar due to being subject to the same climate policy ambition. In 2050, GHG emission in the residential sector is 5 million tonnes CO_2-eq lower due to large-scale electrification of heating and cooking. The observed increase in GHG emissions from the transport sector is due to the previously mentioned increased consumption of LPG. In the service and industrial sectors, higher emissions result from increased consumption of natural gas and oil. Similarly, the variations in fuel consumption within each sector also lead to the differences in GHG emissions before 2050, due to the level of deployment of DSR measures in the residential and transport sectors.

4.6. Differences in system costs

The introduction of DSR (in LGHG_DSR) results in the total annual energy system costs being lower than the reference case from 2030 (Fig. 14). From 2040, investments in the residential sector are further reduced by the increased adoption of more efficient heat pumps (with DSR), instead of natural gas and hydrogen-fuelled boilers. Meanwhile, investments in the transport sector are also reduced by the lower adoption of electric LDVs, to avoid the increase in inflexible charging loads. On the supply side, as the flexibility of the energy system increases with growing shares of smart appliances and passenger EVs, more nuclear power is deployed from 2030 due to the demand profile being smoothened by the increasing level of DSR, avoiding investment in costly storage capacity. By 2050, more wind power is deployed (with DSR) to reduce investment in relatively higher cost nuclear power plants. As a result, the marginal cost of electricity generation is reduced from £ 112 to £ 106 per MWh, a 5.3% reduction, in winter peak time-slices. The reduction in summer peak time-slices is even more dramatic, up to 56%, with costs reduced from £ 99 to £ 44 per MWh.

Overall, the cost savings to the system are as large as 4.6 billion GBP in 2050 due to the aforementioned avoided costs. The cumulative undiscounted cost saving over the whole modelling period is estimated at 30.9 billion GBP.

5. Conclusions

This study has developed a novel modelling framework in a whole energy systems model, UKTM, to investigate the benefits of flexibility, through the use of DSR with smart appliances and passenger EVs, for the low carbon transition. Demand-side flexibility via DSR has been shown to considerably reduce electricity costs relative to a reference case without DSR. This is achieved by demand-side flexibility reducing peak loads and smoothening out the demand load profiles so that increasing low-carbon generation can be deployed. By 2050, significantly more VRE, approximately 11 GW is installed, thereby reducing electricity costs, compared to a case without DSR. Meanwhile, the requirement of additional investment in storage technology and back-up power is also reduced. The introduction of DSR is therefore assessed to help ensure more affordable electricity in a future low-carbon energy system.

With a high penetration of DSR measures in the residential and transport sectors, the total energy system costs saved amounts to approximately 4.6 billion GBP (1.03%) in 2050. Over the whole modelling period, costs of 30.9 billion GBP (undiscounted) can be saved. Earlier adoption of smart systems at scale across the end-use sectors might thus be able to further reduce total system costs.

Even though the policies to introduce demand-side flexibility are

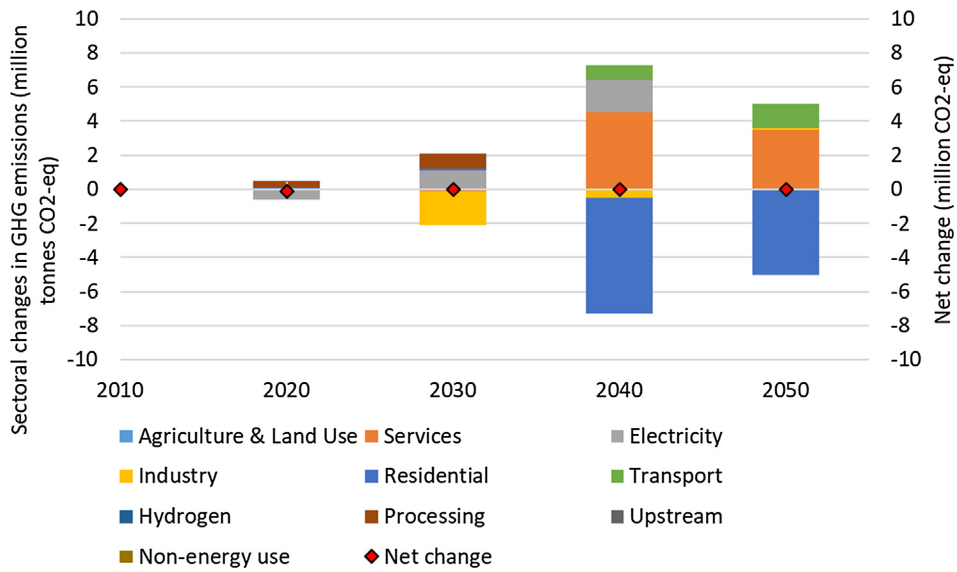

Fig. 13. Sectoral changes in GHG emissions (million tonnes CO_2-eq) between cases with and without DSR (LGHG_DSR – LGHG_Ref).

already in place [10,11,53] in the UK, the implementation approaches and strategies are still not clear. It is thus crucial that policy-makers better understand the possible roadmaps available to encourage consumers to adopt smart appliances and passenger EVs while ensuring the smart control mechanisms and ICT infrastructure can be deployed in time to harness the flexibility potentials from those DSR measures. Extra incentives might also be needed to increase consumers' participation in the smart control schemes.

There are a number of areas for further research. The time resolution used in UKTM is relatively coarse, and therefore it is not possible to model some of the more extreme imbalances between electricity supply and consumption. Future research should explore how a higher temporal resolution can be implemented in the same modelling framework to assess the benefits of DSRs. Moreover, the randomness and heterogeneity of demand patterns can also be taken into account to verify the feasibility of the determined pathways. Furthermore, smart systems in other sectors, such as service and industrial sectors, should also be taken into account to identify the full potential of the demand-side flexibility in the UK energy system. Finally, an increased focus on the implementation rates of smart systems should also be considered to improve the representation of smart system introduction.

This study is a useful starting place, as a first effort to investigate the benefits of the demand-side flexibility from smart appliances and EVs across the whole energy system in the UK. This has not only assessed flexibility in a single year as in previous studies, but also the inter-temporal impact of DSR across modelling years. As a result, the dynamic relationship between substitute technologies within each sector and fuel-switching among sectors has been explored endogenously in this new modelling framework. The impacts of the flexibility of smart systems have thus been reflected and provide an approach suitable for other whole ESMs that need to start incorporating this important option for mitigation.

Acknowledgements

The authors would like to thank the Engineering and Physical Science Research Council (EPSRC) for providing the funding for this work under the Whole Systems Energy Modelling Consortium (WholeSEM) project (EP/K039326/1). This research has also received funding through REEEM project from the European Union's Horizon 2020 research and innovation programme under grant agreement 691739.

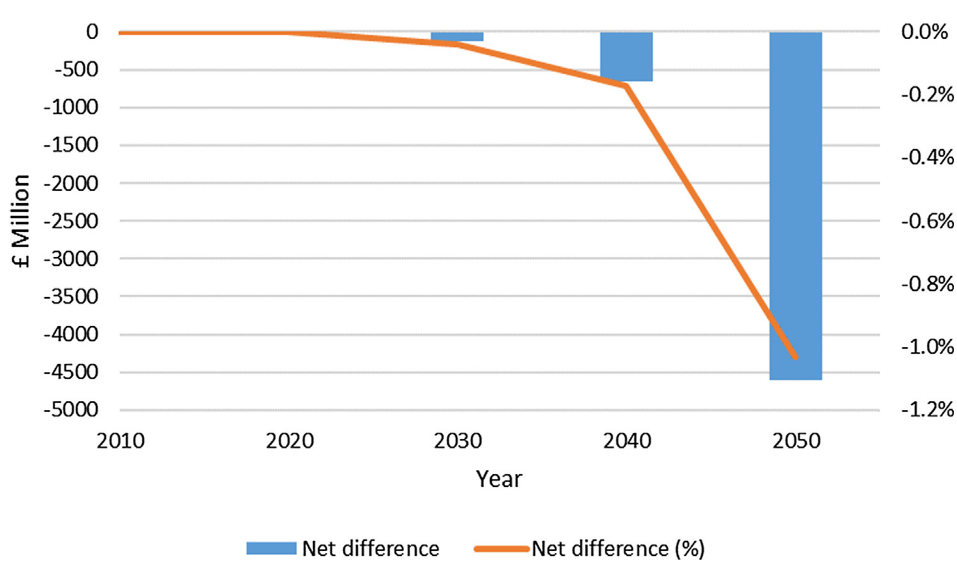

Fig. 14. Differences of undiscounted energy system costs between cases with and without DSR (LGHG_DSR – LGHG_Ref).

References

[1] HM Government. Climate change act 2008. London, UK: HMSO; 2008.
[2] Usher P, Strachan N. UK MARKAL modelling – examining decarbonisation pathways in the 2020s on the way to meeting the 2050 emissions target. London (UK): UCL Energy Institute; 2010 [accessed 2nd July 2018]. http://discovery.ucl.ac.uk/1298585/1/CCC%20MARKAL%20Final%20Report%20-%20UCL%20Nov10.pdf.
[3] Committee on Climate Change. The fifth carbon budget: the next step towards a low-carbon economy. London (UK): Committee on Climate Change; 2015 [accessed 2nd July 2018]. https://www.theccc.org.uk/wp-content/uploads/2015/11/Committee-on-Climate-Change-Fifth-Carbon-Budget-Report.pdf.
[4] IEA. World energy outlook 2017. Fr: Int Energy Agency Paris; 2017.
[5] National Grid. Future energy scenarios. Warwick (UK): National Grid plc; 2017 [accessed 2nd July 2018]. http://fes.nationalgrid.com/media/1253/final-fes-2017-updated-interactive-pdf-44-amended.pdf.
[6] Strbac G. Demand side management: benefits and challenges. Energy Policy 2008;36:4419–26. http://dx.doi.org/10.1016/j.enpol.2008.09.030.
[7] Strbac G, Aunedi M, Pudjianto D, Teng F, Djapic P, Druce R, et al. Value of flexibility in a decarbonised grid and system externalities of low-carbon generation technologies; 2015, doi:10.13140/RG.2.1.2336.0724.
[8] Sanders D, Hart A, Ravishankar M, Brunert J, Strbac G, Aunedi M, et al. An analysis of electricity system flexibility for Great Britain. London (UK): Carbon Trust and Imperial College London Report; 2016 [accessed 2nd July 2018]. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/568982/An_analysis_of_electricity_flexibility_for_Great_Britain.pdf.
[9] Department for Business Energy & Industrial Strategy. Energy Consumption in the UK. London (UK); 2017 < https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633503/ECUK_2017.pdf > [accessed 2nd July, 2018].
[10] Ofgem. Transition to smart meters; 2017 < https://www.ofgem.gov.uk/electricity/retail-market/metering/transition-smart-meters > [accessed December4, 2017].
[11] Ofgem. Upgrading our energy system: smart systems and flexibility plan; 2017 < https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633442/upgrading-our-energy-system-july-2017.pdf > [accessed 2nd July 2018].
[12] Poncelet K, Delarue E, Duerinck J, Six D. Impact of temporal and operational detail in energy-system planning models. TME Work Paper - Energy Environ 2015;162:631–43.
[13] Krakowski V, Assoumou E, Mazauric V, Maïzi N. Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: a prospective analysis. Appl Energy 2016;171:501–22. http://dx.doi.org/10.1016/j.apenergy.2016.03.094.
[14] Hurley D, Peterson P, Whited M. Demand response as a power system resource. Cambridge (USA): Synapse Energy Economics, Inc.; 2013 [accessed 2nd July 2018]. http://www.synapse-energy.com/Downloads/SynapseReport.2013-03.RAP.US-Demand-Response.12-080.pdf.
[15] Haider HT, See OH, Elmenreich W. A review of residential demand response of smart grid. Renew Sustain Energy Rev 2016;59:166–78. http://dx.doi.org/10.1016/j.rser.2016.01.016.
[16] Frontier Economics and Sustainability First. Demand side response in the domestic sector—a literature review of major trials frontier economics and sustainability first. London (UK); 2012 < https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48552/5756-demand-side-response-in-the-domestic-sector-a-lit.pdf > [accessed 2nd July 2018].
[17] Fehrenbach D, Merke IE, McKenna R, Kar IU, Fichtner W. On the economic potential for electric load management in the German residential heating sector - an optimising energy system model approach. Energy 2014;71:263–76. http://dx.doi.org/10.1016/j.energy.2014.04.061.
[18] Drysdale B, Wu J, Jenkins N. Flexible demand in the GB domestic electricity sector in 2030. Appl Energy 2015;139:281–90. http://dx.doi.org/10.1016/j.apenergy.2014.11.013.
[19] Nistor S, Wu J, Sooriyabandara M, Ekanayake J. Capability of smart appliances to provide reserve services. Appl Energy 2015;138:590–7. http://dx.doi.org/10.1016/j.apenergy.2014.09.011.
[20] Stötzer M, Hauer I, Richter M, Styczynski ZA. Potential of demand side integration to maximize use of renewable energy sources in Germany. Appl Energy 2015;146:344–52. http://dx.doi.org/10.1016/j.apenergy.2015.02.015.
[21] Teng F, Aunedi M, Strbac G. Benefits of flexibility from smart electrified transportation and heating in the future UK electricity system. Appl Energy 2016;167:420–31. http://dx.doi.org/10.1016/j.apenergy.2015.10.028.
[22] Gils HC. Economic potential for future demand response in Germany - modeling approach and case study. Appl Energy 2016;162:401–15. http://dx.doi.org/10.1016/j.apenergy.2015.10.083.
[23] Olkkonen V, Rinne S, Hast A, Syri S. Benefits of DSM measures in the future Finnish energy system. Energy 2017;137:729–38. http://dx.doi.org/10.1016/j.energy.2017.05.186.
[24] Aryandoust A, Lilliestam J. The potential and usefulness of demand response to provide electricity system services. Appl Energy 2017;204:749–66. http://dx.doi.org/10.1016/j.apenergy.2017.07.034.
[25] Mahbub MS, Cozzini M, Østergaard PA, Alberti F. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. Appl Energy 2016;164:140–51. http://dx.doi.org/10.1016/j.apenergy.2015.11.042.
[26] Neves D, Pina A, Silva CA. Demand response modeling: a comparison between tools. Appl Energy 2015;146:288–97. http://dx.doi.org/10.1016/j.apenergy.2015.02.057.
[27] Jaramillo LB, Weidlich A. Optimal microgrid scheduling with peak load reduction involving an electrolyzer and flexible loads. Appl Energy 2016;169:857–65. http://dx.doi.org/10.1016/j.apenergy.2016.02.096.
[28] Soares J, Fotouhi Ghazvini MA, Vale Z, deMoura Oliveira PB. A multi-objective model for the day-ahead energy resource scheduling of a smart grid with high penetration of sensitive loads. Appl Energy 2016;162:1074–88. http://dx.doi.org/10.1016/j.apenergy.2015.10.181.
[29] Ayón X, Gruber JK, Hayes BP, Usaola J, Prodanović M. An optimal day-ahead load scheduling approach based on the flexibility of aggregate demands. Appl Energy 2017;198:1–11. http://dx.doi.org/10.1016/j.apenergy.2017.04.038.
[30] Nan S, Zhou M, Li G. Optimal residential community demand response scheduling in smart grid. Appl Energy 2018;210:1280–9. http://dx.doi.org/10.1016/j.apenergy.2017.06.066.
[31] Erdinc O. Economic impacts of small-scale own generating and storage units, and electric vehicles under different demand response strategies for smart households. Appl Energy 2014;126:142–50. http://dx.doi.org/10.1016/j.apenergy.2014.04.010.
[32] Pina A, Silva C, Ferrão P. The impact of demand side management strategies in the penetration of renewable electricity. Energy 2012;41:128–37. http://dx.doi.org/10.1016/j.energy.2011.06.013.
[33] Pina A, Baptista P, Silva C, Ferrão P. Energy reduction potential from the shift to electric vehicles: the Flores island case study. Energy Policy 2014;67:37–47. http://dx.doi.org/10.1016/j.enpol.2013.07.120.
[34] Kwon PS, Østergaard P. Assessment and evaluation of flexible demand in a Danish future energy scenario. Appl Energy 2014;134:309–20. http://dx.doi.org/10.1016/j.apenergy.2014.08.044.
[35] Loulou R, Lehtila A, Kanudia A, Remme U, Goldstein G. Documentation for the TIMES model: Part II. IEA-Energy Technology Systems Analysis Program; 2016 [accessed 2nd July 2018]. https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-II_July-2016.pdf.
[36] Daly HE, Fai sB. UK TIMES model overview 2014 < http://www.ucl.ac.uk/energy-models/models/uktm-ucl/uktm-documentation-overview > [accessed November28, 2017].
[37] Department of Energy & Climate Change. Digest of United Kingdom energy statistics 2011. London (UK); 2011 < http://webarchive.nationalarchives.gov.uk/20120403141252/https:/www.decc.gov.uk/assets/decc/11/stats/publications/dukes/2312-dukes-2011–full-document-excluding-cover-pages.pdf > [accessed 2nd July 2018].
[38] Committee on Climate Change. Carbon budgets: how we monitor emissions targets; 2018 < https://www.theccc.org.uk/tackling-climate-change/reducing-carbon-emissions/carbon-budgets-and-targets/ > [accessed 2nd July, 2018].
[39] Zimmermann J-P, Evans M, Griggs J, King N, Harding L, Roberts P, Evans C. Household electricity survey: a study of domestic electrical product usage. Milton Keynes (UK): Intertek Testing & Certification Ltd; 2012 [accessed 2nd July 2018]. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/208097/10043_R66141HouseholdElectricitySurveyFinalReportissue4.pdf.
[40] Deane JP, Chiodi A, Gargiulo M, Gallachóir BPÓ. Soft-linking of a power systems model to an energy systems model. Energy 2012;42:303–12. http://dx.doi.org/10.1016/J.ENERGY.2012.03.052.
[41] Deane JP, Gracceva F, Chiodi A, Gargiulo M, Gallachóir BPÓ. Electrical power and energy systems assessing power system security. A framework and a multi model approach. Int J Electr Power Energy Syst 2015;73:283–97. http://dx.doi.org/10.1016/j.ijepes.2015.04.020.
[42] Sinden G. Characteristics of the UK wind resource: long-term patterns and relationship to electricity demand. Energy Policy 2007;35:112–27. http://dx.doi.org/10.1016/j.enpol.2005.10.003.
[43] Summerfield AJ, Oreszczyn T, HamiltonI G, Shipworth D, Huebner GM, Lowe RJ, et al. Empirical variation in 24-h profiles of delivered power for a sample of UK dwellings: implications for evaluating energy savings. Energy Build 2015;88:193–202. http://dx.doi.org/10.1016/j.enbuild.2014.11.075.
[44] UK Power Networks - Low Carbon London n.d. < http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Low-Carbon-London-(LCL)/ > [accessed November28, 2017].
[45] Department for Transport. Road traffic estimates: Great Britain 2016; 2017 < https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/611304/annual-road-traffic-estimates-2016.pdf > [accessed 2nd July 2018].
[46] Hong J, Kelly NJ, Richardson I, Thomson M. Assessing heat pumps as flexible load. Proc Inst Mech Eng Part A J Power Energy 2013;227:30–42. http://dx.doi.org/10.1177/0957650912454830.
[47] Zehir MA, Bagriyanik M. Demand Side Management by controlling refrigerators and its effects on consumers. Energy Convers Manage 2012;64:238–44. http://dx.doi.org/10.1016/j.enconman.2012.05.012.
[48] Stötzer M, Gronstedt P, Styczynski Z. Demand side management potential a case study for Germany. In: CIRED 21st international conference on electricity distribution, Frankfurt, Germany, June 6–9; 2011.
[49] Mert W, Suschek-Berger J, Tritthart W. Consumer acceptance of smart appliances. In: WP5 Report from Smart-A Project; 2008 < https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/smart-a_consumer_acceptance.pdf > [accessed 2nd July 2018].
[50] Department for Business, Energy & Industrial Strategy. Smart meters implementation programme 2017 progress update; 2018 < https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/671930/Smart_Meters_2017_update.pdf > [accessed 2nd July 2018].

[51] Department for Environment Food & Rural Affairs, Department for Transport. UK plan for tackling roadside nitrogen dioxide concentrations: an overview. London (UK); 2017 < https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633269/air-quality-plan-overview.pdf > [accessed 2nd July 2018].
[52] Department for Business, Energy & Industrial Strategy. Coal Generation in Great Britain - The pathway to a low-carbon future: consultation document. London (UK); 2016 < https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/577080/With_SIG_Unabated_coal_closure_consultation_FINAL__v6.1_.pdf > [accessed 2nd July, 2018].
[53] Department for Business, Energy & Industrial Strategy. The clean growth strategy: leading the way to a low carbon future. London (UK); 2017 < https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf > [accessed 2nd July 2018].