

Modelling Real-Time Pricing Demand Response in a Long-Term Whole Energy System Model, UK TIMES

by

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Abstract

UK energy system should be transformed dramatically to achieve the ambitious 2050 GHG reduction target, which is to reduce 80% GHG emissions on 1990 level by 2050. With a higher penetration rate of VRE and nuclear power, flexibility measures, such as demand response (DR), are essential to balance electricity supply and demand in the future. However, consumers' behavioural changes for real-time pricing DR has majorly been modelled only in power systems, rather than modelled in whole energy systems. The influences in a long-term whole energy system have not been fully explored. Therefore, this study developed a modelling framework in UK TIMES model to incorporate DR for long-term energy planning to investigate the advantages of DR in future UK low-carbon energy system. The results of a scenario with DR were compared to those of a scenario without DR to reveal the influences. According to the results, residential energy service demands in peak-load time-slices are shifted to reduce electricity consumption and to balance electricity supply and demand. More heat pumps are deployed to improve system flexibility and to further decarbonise residential heating. On the supply side, wind and storage technologies are more active while less electricity is generated by nuclear power. As a result, in 2050, GHG emissions can be further reduced by 1.8 million metric tones of CO₂eq (about 1% less) and total system costs is about 835 million GBP less (about 0.18% cheaper). However, the influences are relatively small. Further sensitivity studies are essential to verify the robustness of the conclusion.

1. Introduction

To meet the UK 2050 decarbonisation target, whole UK energy system should be transformed dramatically by adopting low-carbon technologies in both energy supply and demand sectors. In the UK, electricity generation alone was responsible for 31 percent of greenhouse gas emissions in 2014 (DECC, 2016a). Low-carbon power

technologies, such as PV and wind turbines, should thus be deployed on a significant scale to reduce the GHG emissions from electricity generation. With the high penetration rate of variable renewable energy (VRE) in the future system, it is crucial to improving system flexibility to ensure the electricity supply stability. Demand response (DR) is one of the major measures should be taken into account to accommodate VRE and to balance energy supply and demand. An energy system model should thus incorporate the dynamics of DR to determine the optimal strategy of demand-side management.

Although many studies have been done to develop models for DR, most of those studies were only focus on power market or electricity system (Pallonetto et al., 2016; Rahmani-andebili, 2016; Neves et al., 2015). The influences of demand-side technologies were often neglected or represented by a limited number of predefined development scenarios. Therefore, only the benefits for supply-side technologies were fully explored. The complicated interaction between DR and energy demand technologies, such as electric vehicles or heat pumps, cannot be well represented in those models. This study thus aims to develop a modelling framework for DR in a whole energy system model, UK TIMES (UKTM) model, which includes all energy supply and demand sectors in the UK. As a result, not only the influences on the supply-side technologies can be evaluated, but also the impacts on demand-side technologies can be determined.

DR measures can be price-based or incentive-based. Price-based measures include Real Time Price (RTP), Critical Peak Price (CPP) and Time of Use Tariff (TOU). As for incentive-based, where the participating customers are rewarded for reducing their load when requested by an aggregator or TSO (Pallonetto et al., 2016). More automatic DR measures, such as direct load control, would require additional communication infrastructure in place; therefore, those measures will be available in the farther future. In the near- to medium-term, DR measures depending on consumers' behaviour would be carried out first to improve the system flexibility. To evaluate the benefits to the whole energy systems, consumers' responses should react to the real-time pricing signals to lower the total system costs, such as lowering peak-load demand to reduce the consumption of electricity with higher costs. Therefore, the purposes of this study are twofold.

1. Develop a modelling framework for real-time pricing DR in a long-term energy planning model.
2. Evaluate the benefits of DR in the whole energy system, including supply and demand sides.

This paper is organised as follows: The adopted energy model (UKTM model) is briefly introduced, followed by the explanation of the proposed modelling framework in the TIMES model, which is a linear programming optimisation model. The adopted price elasticities for demand response are then addressed. Scenarios with and without DR in intra-day timeslots are then applied to the proposed model to investigate the impacts on the whole energy system. Finally, the benefits and influences on both supply-side and demand-side technologies are explored.

2. UK TIMES (UKTM) Model

UKTM (Daly and Fais, 2014) has been developed by the UCL Energy Institute as the successor to the UK MARKAL model (Kannan et al., 2007). It is based on the model generator TIMES (The Integrated MARKAL-EFOM System) (Loulou et al., 2016), which is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) (IEA, 2015). Besides its academic use, UKTM is the central long-term energy system pathway model used for policy analysis at the Department for Business, Energy & Industrial Strategy (BEIS) (DECC, 2016b) and the Committee on Climate Change (CCC) (CCC, 2015).

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. The model is comprised of three supply-side sectors (resources & trade, processing & infrastructure and electricity generation) and five demand-side sectors (residential, services, industry, transport and agriculture). The simplified reference energy system is illustrated in Figure 1. All sectors are calibrated to the base year 2010 to be consistent with the official energy statistics (DECC, 2011), including the existing stock of energy technologies and their characteristics. 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. The future technology parameters are based on UK domestic studies or reports of major international organisations. Furthermore, the model also includes assumptions for attributes not directly connected to individual technologies, such as energy import prices, resource availability and the potentials of renewable energy sources. The temporal variations of energy supply and demand are represented in 16 time-slices (four intra-day time-slices in four seasons). The definitions of these time-slices are presented in Table 1. In addition to all energy flows, emissions of CO₂, CH₄, N₂O and HFC from energy use are accounted for. UKTM minimises total welfare costs (under perfect foresight) to meet the exogenously defined energy demands under a range of input assumptions (e.g. technology parameters are drivers of energy demand (GDP and population

growth, for example)) and additional constraints (such as maximum technology penetration rates and deployment potentials). The model delivers a cost optimal, system-wide solution for the energy transition over the coming decades (Fais et al., 2016).

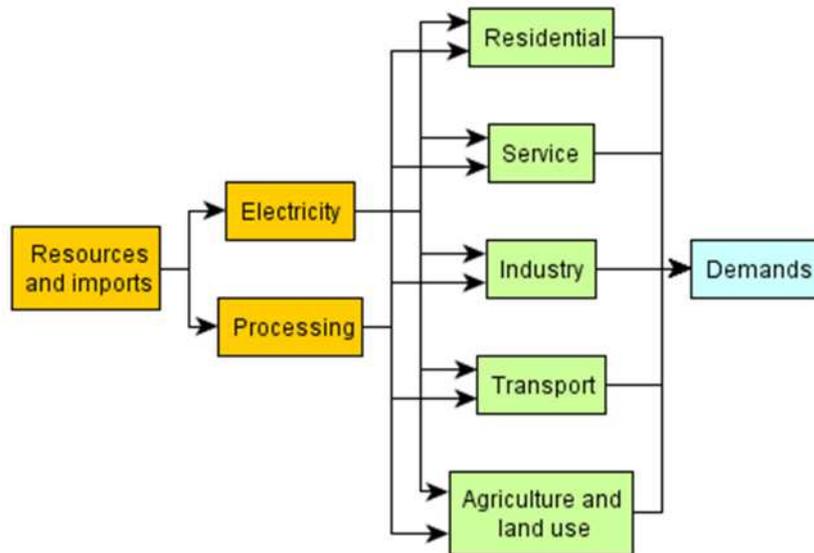


Figure 1. Simplified reference energy system of the UK energy system in UKTM

Table 1. Definitions of time-slices in UKTM

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

3. Demand Response Modelling

Although the existing mechanism for elastic demand in the TIMES model can reflect consumers' reaction to pricing signals, the reduced energy service demand (ESD) cannot be shifted to other time-slices as demand-shifting for demand response modelling. An additional mechanism is thus introduced into TIMES model to model the consumers' behaviour of demand shifting based on the elastic demand mechanism. The existing mechanism for elastic demand and the newly introduced mechanism are explained briefly in this section.

In the standard version of TIMES model, the ESDs are determined exogenously and are treated as constant values in the model. The model then determines the optimal combination of technologies to fulfil the required demands with the lowest cost. However, consumers would change their demands of services, such as heating, lighting, and etc., if they are exposed to pricing signals. With a higher price, they might reduce the demands to avoid high energy bills. TIMES model thus incorporates the following equation to reflect consumers' behaviour on pricing signals.

$$\frac{DM_i}{DM_i^0} = \left(\frac{p_i}{p_i^0}\right)^{E_i} \quad (1)$$

Where DM_i is the ESD i and DM_i^0 is the original value before changed corresponding to varied pricing signal. p_i is the price required to provide unit ESD i and p_i^0 is the original price in reference case. E_i is the own price elasticity of demand i . The elasticity is usually based on empirical evidence. With higher elasticity, demand would be more sensitive to pricing signals.

In TIMES model, ESDs are introduced into the model as exogenously determined constants which should be satisfied by end-use technologies, such as vehicles, lamps, or heaters. ESDs are converted into variables to vary with the supplying cost of services. The original model is then transformed into an equivalent formulation and integrated into the following equations to simplify the optimisation problem. Consequently, the revised model can be approximated by linearisation techniques. The detailed derivation procedure can be found in the manual of TIMES model (Loulou et al., 2016). The transformed equivalent model is illustrated as follows.

$$\text{Max } \sum_i \sum_t \left(p_i^0(t) \cdot DM_i^0(t)^{\frac{1}{E_i}} \times \frac{DM_i(t)^{1+\frac{1}{E_i}}}{\left(1+\frac{1}{E_i}\right)} \right) - c \cdot X \quad (2-1)$$

$$\text{s. t. } \sum_k CAP_{k,i}(t) \geq DM_i(t) \quad i = 1, \dots, I; t = 1, \dots, T \quad (2-2)$$

$$B \cdot X \geq b \quad (2-3)$$

X is the vector of all TIMES variables and c is the associated cost vector. $CAP_{k,i}(t)$ is the available capacity of technology k , which can provide energy service i , in time-slice t . The first term in equation (2-1) represents the change of welfare costs for the elastic demands. The second term in the same equation determine the total system costs. Equation (2-2) ensures all elastic demands can be satisfied by end-use technologies. Equation (2-3) represents the rest of system constraints.

Consumers' might shift demand from a particular time-slice with a higher price to other

time-slices with lower prices in order to reduce the total amount of energy bills. This mechanism can be modelled based on the original formulation for elastic demands in TIMES model. However, the original framework does not consider demand-shifting which allows reduced demand to be shifted to other time-slices while maintaining the total amount of demands. Therefore, additional constraints are built into the model to deal with the demand-shifting modelling. The constraints are formulated as follows and explained below.

$$DM_i(s, dt) - DM_i^0(s, dt) = -1 \cdot \sum_{at} (DM_i(s, dt) - DM_i^0(s, dt))$$

$$\text{if } DM_i(s, dt) < DM_i^0(s, dt) \quad s = 1, \dots, 4; dt = D, P, E, N \quad (3)$$

Where s is the season in a year; dt is the diurnal time-slice representing a period of time in a typical day. The constraints ensure that the shifted demand in a time-slice is equal to the summation of the changed amount of demands in other time-slices in the same season. The constraints are only applied to time-slices with reduced demands.

4. Short-run Elasticity

Since this study focuses on intraday demand response, short-run price elasticity of residential electricity demand should be applied. There have been numerous studies focused on determining short-run price elasticity of residential electricity demand. Some selected studies are listed in Table 2. The short-run elasticity ranges widely from -0.02 to -0.58 in the literature. For demonstration, this study sets price elasticities of residential service demands in the range of -0.15 to -0.25.

Table 2. Literature on price elasticity of residential electricity demand

Author	Year	Region	Short-run elasticity
Bohi and Zimmerman	1984	US	-0.2
Kamerschen and Porter	2004	US	-0.13
Bernstein and Griffin	2005	US	-0.04 to -0.31
Paul et al.	2009	US	-0.05 to -0.21
Alberini & Filippini	2011	US	-0.08 to -0.15
Narayan and Smyth	2005	Australia	-0.26
Beenstock et al.	1999	Israel	-0.21 to -0.58
Ziramba	2008	South Africa	-0.02
Halicioglu	2007	Turkey	-0.33
Okajima and Okajima	2013	Japan	-0.305 to -0.493

5. Results and Discussions

This study focused on consumers' DRs to pricing signals. Therefore, only those ESDs in the residential sector were taken into account, including space heating, water heating, cooking, lighting, cloth-washing, dish-washing, and entertaining (TV, DVD, and etc.). It was assumed that smart meters are available in all households to deliver pricing signal in real-time. Three scenarios were analysed in this study to reveal the influences of DR on the UK energy system. The definitions of the scenarios are listed in Table 3.

Table 3. Definitions of scenarios

Scenario	GHG targets	DSR settings
BASE	No GHG reduction target	No demand response
LGHG_NODSR	80% reduction on 1990 level by 2050 Carbon budgets (1 st to 5 th)	No demand response
LGHG_DSR	80% reduction on 1990 level by 2050 Carbon budgets (1 st to 5 th)	demand response with real-time pricing

In BASE scenario, UKTM determined the optimal technology mix to fulfil future energy demands only based on cost-effective factors. As for LGHG_NODSR scenario, UKTM introduced abundant low-carbon technologies, such as wind and nuclear power, into the system to decarbonise the whole energy system to reach 2050 target. UKTM further took the effects of DR into account in LGHG_DSR scenario. The elastic demands for LGHG_DSR were estimated by comparing energy prices in the new scenario with those of BASE case.

To explore the influences of consumers' DR, the differences of modelling results between LGHG_DSR and LGHG_NODSR are presented in Figure 2 to Figure 8 and Table 4. Since the electricity is more expensive in LGHG_DSR than in BASE case, consumers would shift time-of-use of appliances and replace residential technologies to reduce electricity bills. It has also been found that the system flexibility can be improved by applying DR measures, adopting more flexible technologies, such as heat pumps, and reducing electricity generation from nuclear power. Consequently, GHG emissions can be further decarbonized with cheaper total system costs although the changes are limited. The more detailed results are discussed in the following sections.

As shown in Figure 2, ESDs in the residential sector are shifted from time-slices with higher energy price to time-slices with relatively lower prices. In both 2030 and 2050, ESDs during peak-load hours are majorly reduced and shifted to other time-slices

since the energy cost during peak-load hours is usually higher than the costs in other time-slices. One of the exceptions is the ESD-shifting during peak-load hours in 2030 winter (2030-WP) which is much higher. In that time-slice, the electricity cost is lower than that in BASE case for replacing some expensive electricity from biomass-fueled plants and CHP in the process sector with cheaper electricity from gas-fired power plants. Furthermore, more space heating is provided by gas heaters rather than electric heaters. It is also evident that ESDs are usually higher in summer-peak time-slice (2030-SP and 2050-SP). During the summer time, electricity consumption is generally lower than in other seasons which means the generation cost could also be lower. The ESDs thus increase to reduce the differences between peak-loads in each season so that the capacity factors of power plants could be higher to reduce the marginal costs.

The annual differences of activities of residential technologies are presented in Figure 3. Fewer space heat is provided by night storage heaters (RH-ELC) to reduce electricity consumption. Instead, more heat is supplied by gas heaters (RH-GAS) and more efficient heat pumps (RH-HP). On the other hand, fewer hot water is provided by gas water heaters (RW-GAS), which is replaced by electric water heaters (RW-ELC). However, by 2050, activities of gas heaters are further reduced and replaced by heat pumps to achieve 2050 GHG target.

Due to the variations of technology usages, fuel consumption in the residential sector changes accordingly, as shown in Figure 4. Electricity consumption is reduced in almost all the modelling period except for 2050. Gas consumption is also lower. The reduction of electricity consumption in LGHG_DSR is because of the higher electricity costs. To achieve the GHG reduction targets, more low-carbon electricity generation technologies, such as wind and PV, are adopted so that the electricity generation costs are higher. The model thus tended to reduce electricity consumption by switching fuel type of residential technologies and by increasing the adoption of higher efficient technologies, such as heat pumps. The reduction of electricity consumption is the result of the replacement of night storage heaters with gas heaters and heat pumps.

On the other hand, the model also reduced gas consumption to lower GHG emissions. Even though the gas consumption increases for the higher activities of gas heaters, the total consumption of gas is reduced for the lower activities of gas water heaters and district heating. By 2050, gas consumption further drops for the sharp reduction of heat generated by gas heaters while more heat produced by heat pumps with low-carbon electricity.

In Figure 5, the difference of electricity consumption in end-use sectors is presented. The fluctuations are majorly from the shifted ESDs in the residential sector. However, it has also been found that pumped hydro storage and battery storage technologies consume more electricity after 2035. Conversely, the transport sector is the only sector drops electricity consumption in 2045 and 2050. As shown in the right chart of Figure 6(a), to decarbonise electricity generation, the share of nuclear are more than half of the hourly electricity supply in 2050 along with other low-carbon technologies. Since nuclear power supplies baseload electricity which cannot vary too much in a short period of time, the system in 2050 becomes less flexible than in 2030. The electricity supply should thus rely on flexible or variable technologies to match the electricity consumption. Pumped hydro storage and battery storage thus charge more electricity in the night and supply more electricity during daytime and peak-load hours. Furthermore, charging storage technologies during the night can also alleviate the fluctuations caused by the reduced adoption of electric vehicles and night storage heaters, which also charge in the night.

As shown in Figure 6(b), electricity supply from fossil fuel power plants is lower for the reduced electricity consumption. Electricity from gas power plants and gas power plants with CCS are the most obvious sources of reduction. As the electricity consumption in the residential sector increases sharply in 2050 for the sharp adoption of heat pumps, more wind turbines are deployed to provide electricity while less electricity is supplied by nuclear power plants for its inflexibility.

The difference of annual primary energy consumption is shown in Figure 7. Due to the fuel switching for heating in the residential sector and less gas consumption for electricity generation, the consumption of natural gas and biomass is reduced significantly in each year. However, the consumption of oil and coal is higher in the LGHG_DSR scenario. More coal is consumed in 2020, 2025, and 2030 for the higher hydrogen consumption in the industrial sector. Changes of adopted technologies in the transport sector lead to the higher oil consumption in 2015, 2045, and 2050. In 2015, gas consumption in shipping is replaced by oil consumption. In 2045 and 2050, on the other hand, electric vehicles are replaced by petrol vehicles to save the investment costs. The replacement causes the increases of oil consumption in both years.

In Figure 8, the difference of total system cost is illustrated. The flow costs represent the costs required to provide fuels. The significant reduction of gas consumption in both the residential sector and electricity generation saves a considerable amount of flow costs. On the other hand, the sharpest increase of investment cost in 2035 is for the heavy investment of new wind turbines. In 2045 and 2050, the investment costs are lower for the fewer adoption of electric vehicles. Consequently, the total system

costs are saved about 431 million GBP in 2030 and 835 million GBP in 2050 respectively in terms of undiscounted costs. The saved costs are about 0.12% and 0.18% in 2030 and 2050 respectively. However, As shown in Table 4, GHG emissions are reduced by about 1.8 million metric tones of CO₂eq, which is about 1% lower than LGHG_NODSR scenario.

Table 4. The annual differences of GHG emissions and total system costs between LGHG_DSR and LGHG_NODR

	2020	2025	2030	2035	2040	2045	2050
Total system costs (M£)	-96	-69	-431	104	-186	-492	-835
GHG emissions (Mt CO ₂ eq)	1.17	0.00	1.31	-1.60	0.40	1.77	-1.88

6. Conclusions

In this study, a new modelling framework in UKTM for consumers' DR to real-time pricing signal has been developed to investigate the influences of DR in the UK energy system.

By adopting DR, consumers are able to shift time-of-use of appliances to reduce electricity bills. As shown in this study, partial of ESDs during peak-load hours are shifted to other time-slices to use cheaper electricity. Furthermore, night storage heaters are replaced by gas heaters and more efficient heat pumps to save electricity consumption. As a result, electricity consumption in the residential sector is lower over the modelling period.

To achieve 2050 GHG reduction target, low-carbon electricity generation technologies, such as nuclear and wind, are adopted enormously to deeply decarbonise electricity generation. As nuclear power provides more than half of the total electricity in 2050, the system is less flexible than it is in the previous years. Therefore, variable or flexible technologies should play a critical role to balance electricity supply and demand. This could be the reason why wind and storage technologies provide more electricity approaching 2050. In contrast, inflexible technology, such as nuclear, is less preferable.

System flexibility can be further improved by adopting more heat pumps and storage technologies while reducing night storage heaters. Even though night storage heaters can charge in the night and supply heat in daytime, night storage heaters are unable to generate electricity to balance the electricity supply and demand. Therefore, more electricity is stored by pumped hydro and battery storage technologies in the night to

be released in the daytime to balance the system. On the other hand, heat pumps can generate heat more efficiently so that consume less electricity. Moreover, heat pumps can be operated more flexibly to match with the pattern of electricity generation from VRE. More VRE can thus be deployed to decarbonise electricity.

The reduction of gas consumption is crucial to reduce both GHG emissions and total system costs. With DR, the residential sector can be further electrified with heat pumps to save abundance amount of electricity and natural gas. Because of the reduction of electricity consumption, gas consumption for electricity generation drops further. As a result, in 2050, the total system costs can be saved up to 835 million GBP while the GHG emissions are about 1.8 million metric tones of CO₂eq less than the case without DR.

Although DR can benefit the whole energy systems for lower costs and GHG emissions, the scales of the differences are still limited. Compared to the case without DR, total costs are dropped by 0.18% and GHG emissions are 1% less than the case without DR. It is thus essential to evaluate the influences of DR with various combinations of parameters, such as elasticity, to draw a more robust conclusion in the future.

Furthermore, for the future study, influences of DR with load control could be investigated to compare with the outcomes of this study to identify the strengths of load control in the whole energy system in terms of cost-saving and GHG reduction.

Acknowledgement

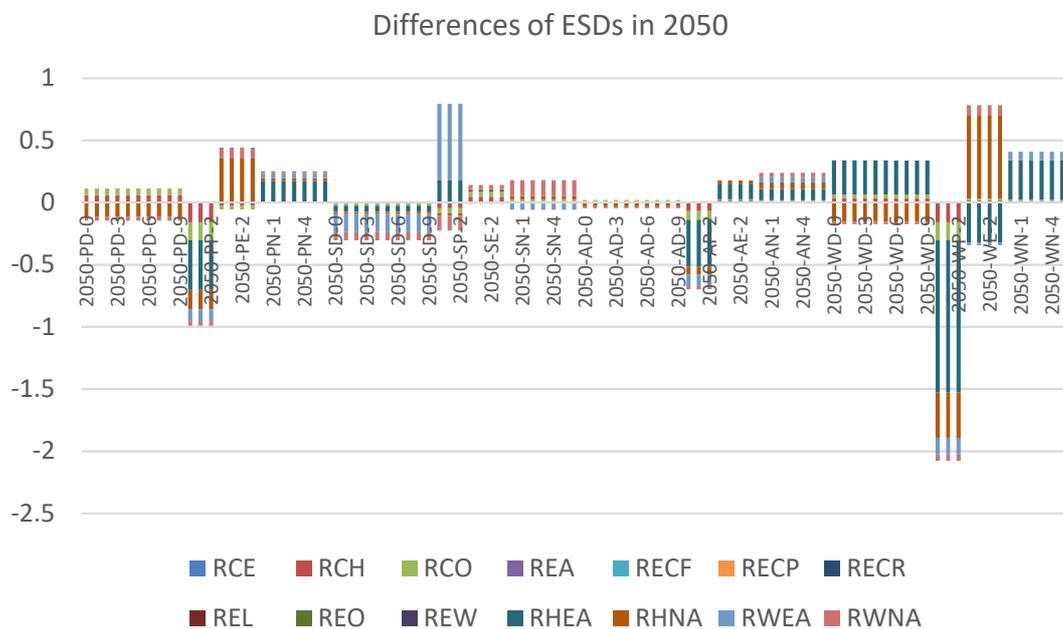
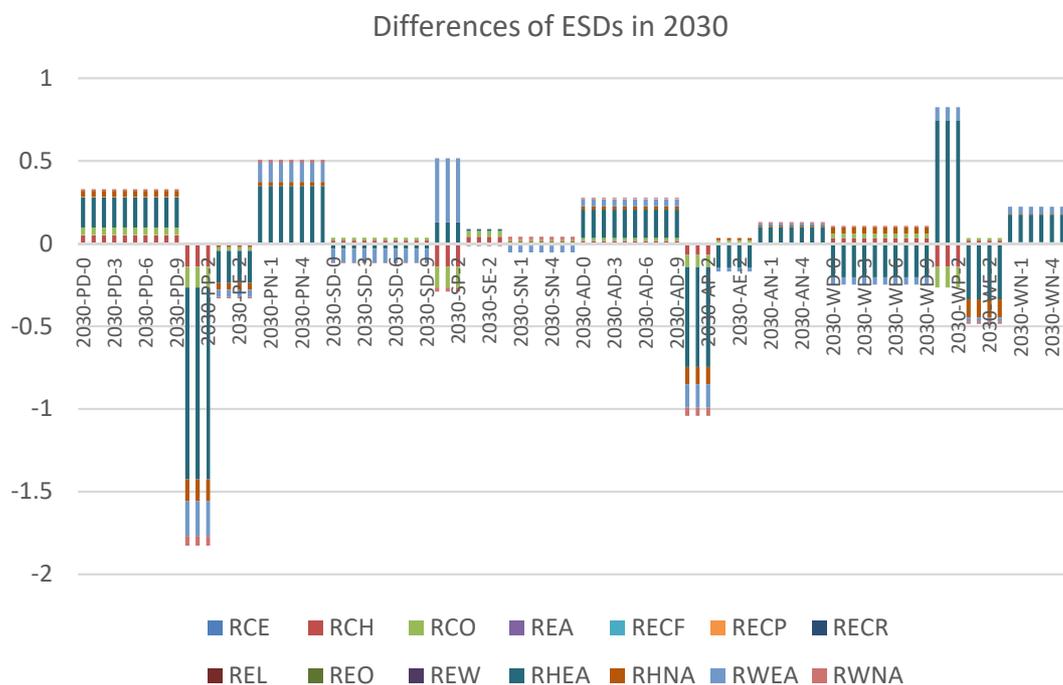
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Figure 2. The differences of hourly energy service demands between LGHG_DSR and LGHG_NODSR



* RCH: cook-hobs; RCO: cook-ovens; RCE: cook-other (kettle and etc.); REA: entertainment (TV, DVD, and etc.); RECF: freezers; RECP: computers; RECR: refrigerators; REL: lighting; REO: other; REW: wet-appliances (washing machine and dishwasher); RHEA: space-heating-existing-house; RHNA: space-heating-new-house; RWEA: hot-water-existing house; RWNA: hot-water-new-house

** 2050-PD-0: year-(time-slice)-(hour index)

Figure 3. Annual differences of activities of residential technologies between LGHG_DSR and LGHG_NODSR

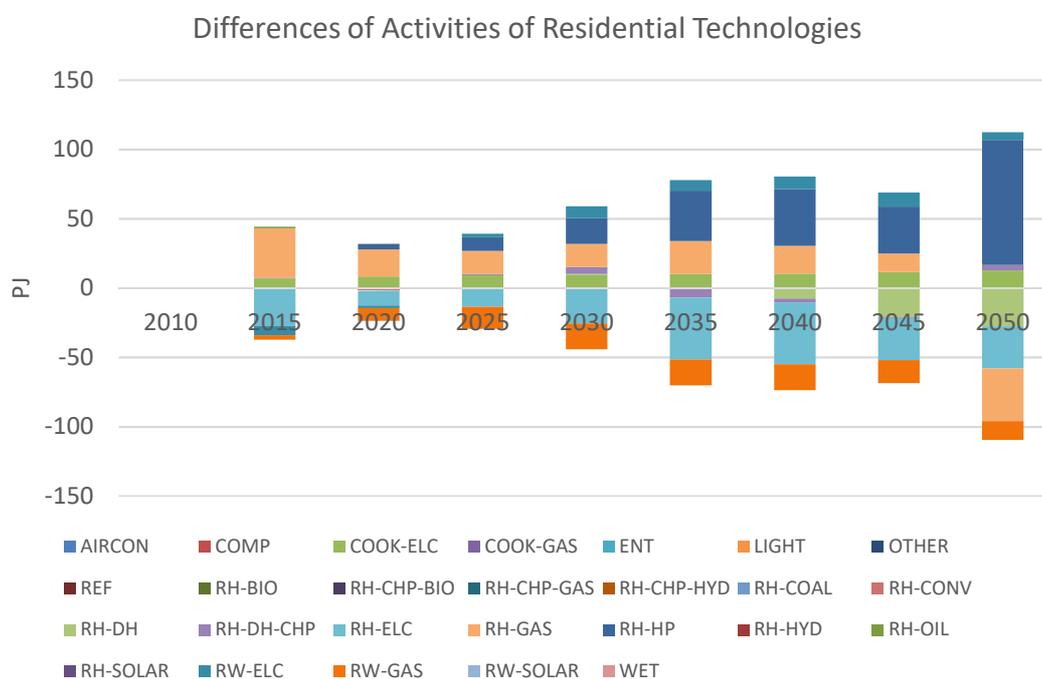


Figure 4. Annual difference of fuel consumption in residential sector between scenarios with and without demand response

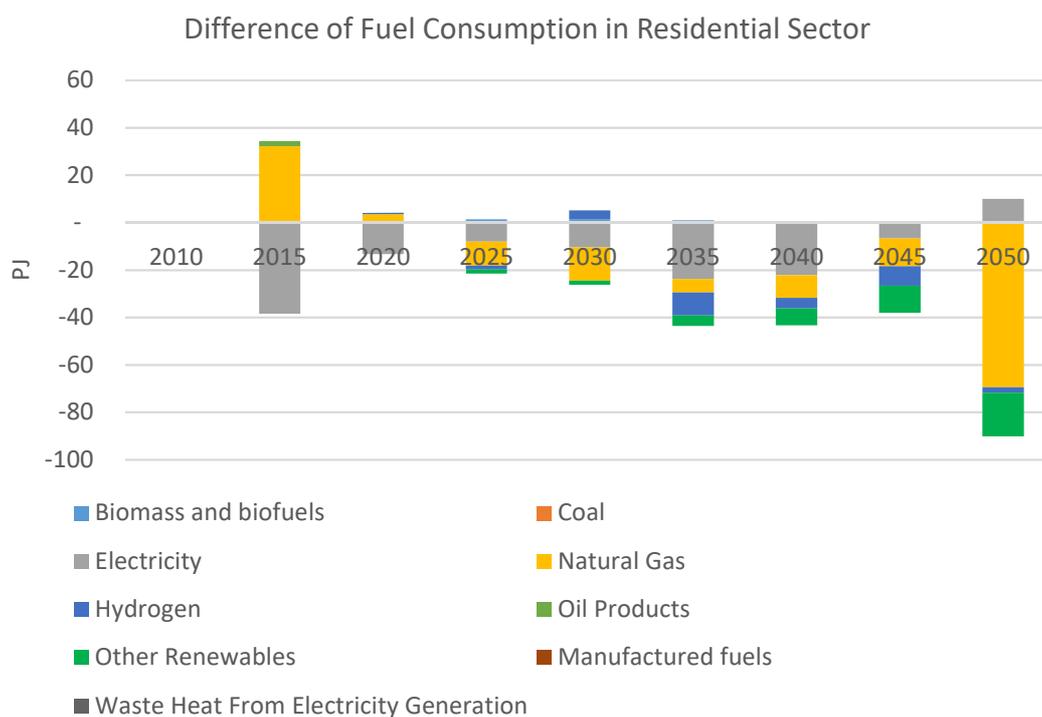


Figure 5. Annual difference of electricity consumption by sector between LGHG_DSR and LGHG_NODSR

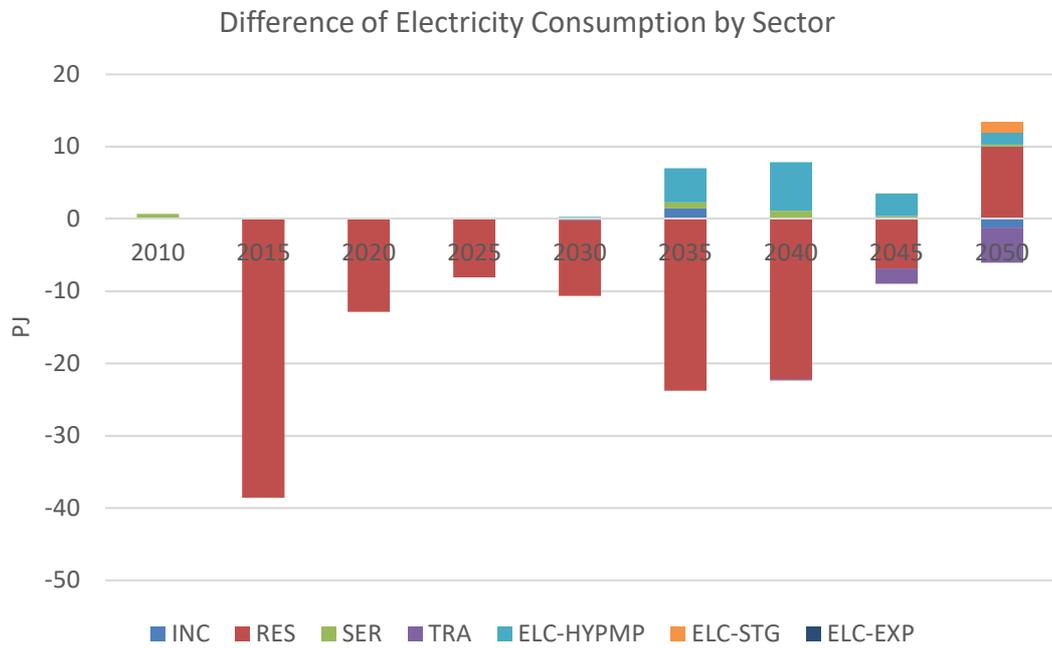
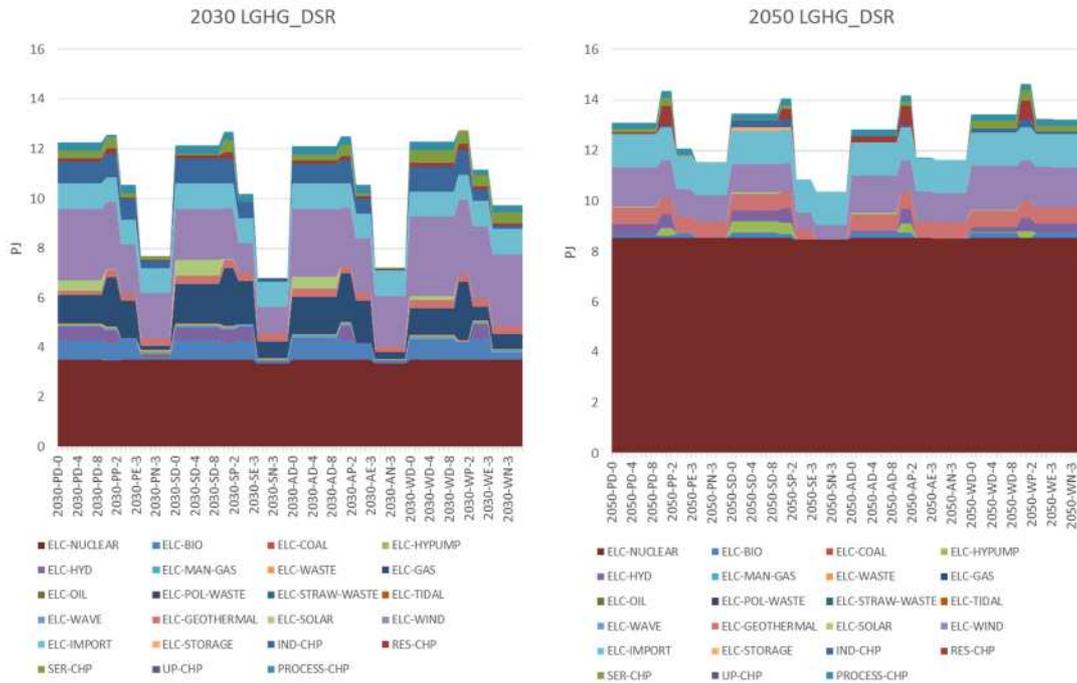
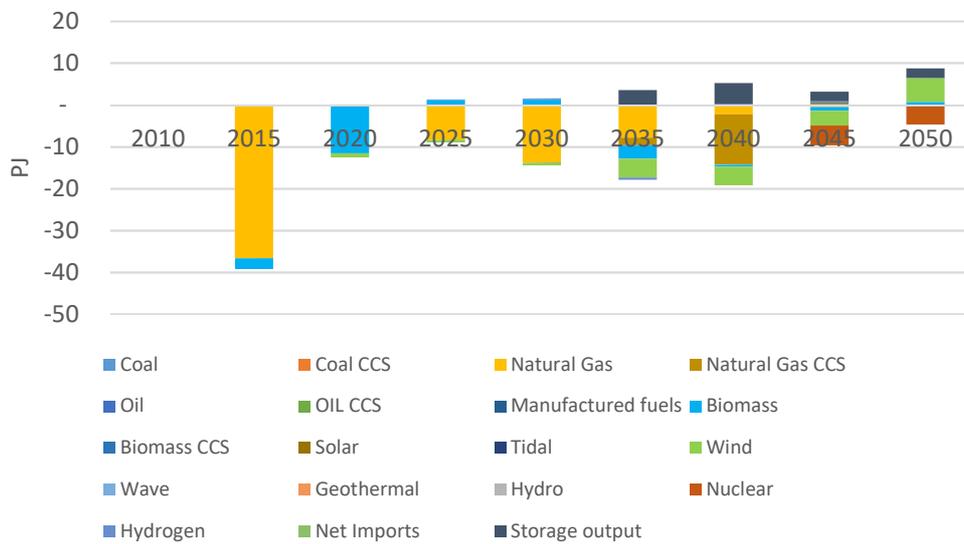


Figure 6. Electricity supply by fuel type for LGHG_DSR and the difference between LGHG_DSR and LGHG_NODSR



(a)

Difference of Electricity Supply by Fuel Type between LGHG_DSR and LGHG_NODSR



(b)

Figure 7. Annual differences of primary fuel consumption between LGHG_DSR and LGHG_NODSR

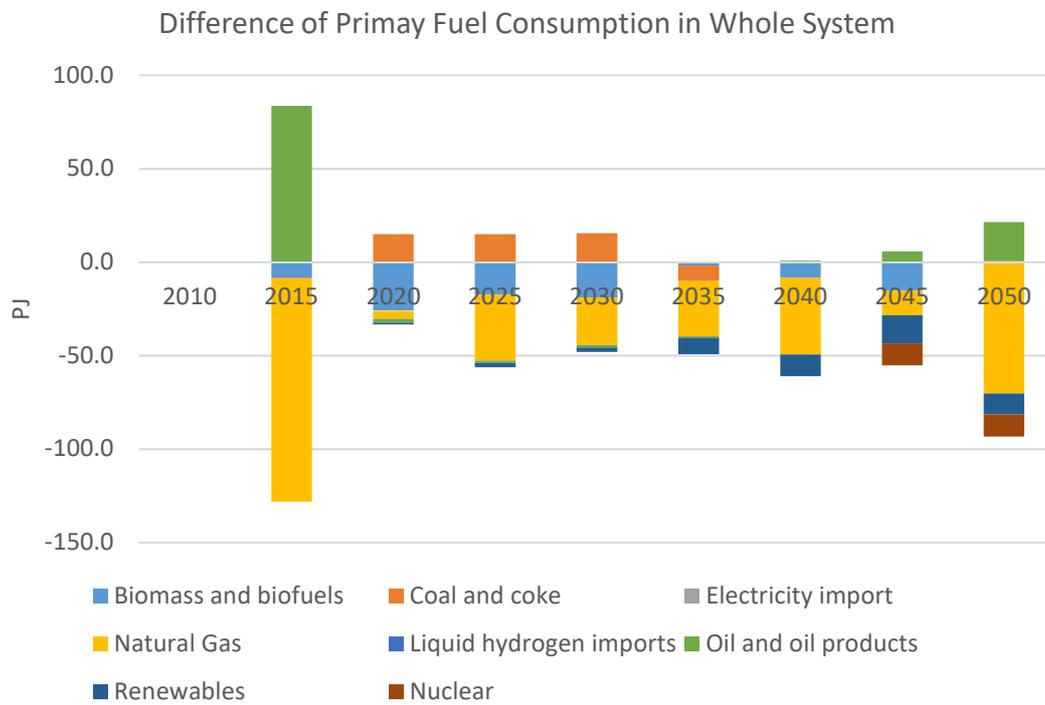
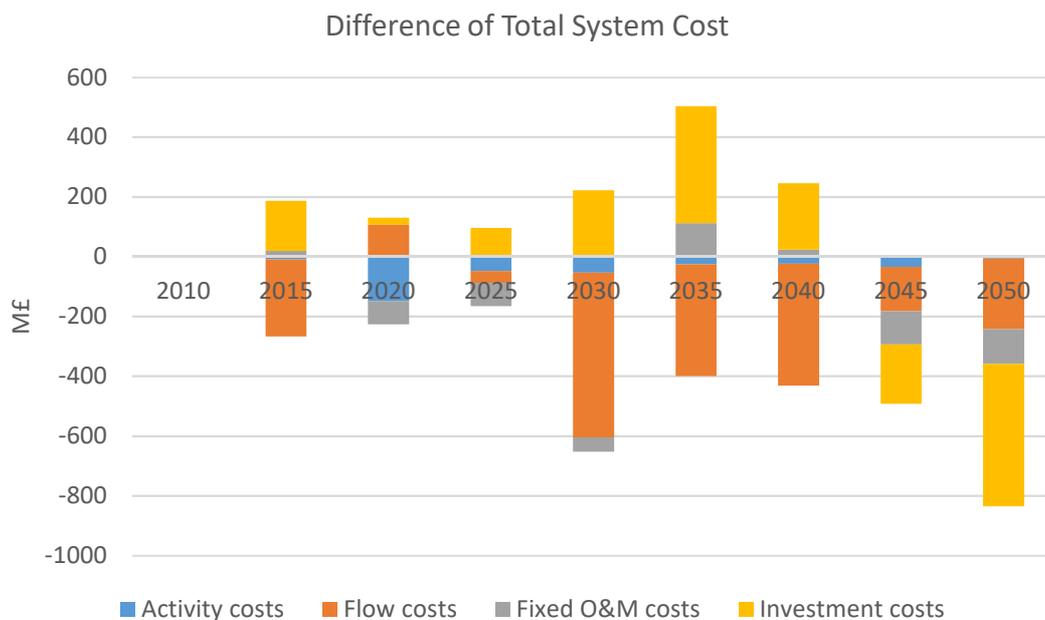


Figure 8. Annual differences of total system cost between LGHG_DSR and LGHG_NODSR



*costs are illustrated in undiscounted terms