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Published in:
Energy

DOI:
10.1016/j.energy.2018.08.210

Published: 01/12/2018

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Olkkonen, V., Ekström, J., Hast, A., & Syri, S. (2018). Utilising demand response in the future Finnish energy system with increased shares of baseload nuclear power and variable renewable energy. *Energy*, *164*, 204-217. https://doi.org/10.1016/j.energy.2018.08.210

Utilising demand response in the future Finnish energy system with increased shares of baseload nuclear power and variable renewable energy

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Abstract:

The research presented in this paper aims to assess the technical effectiveness of demand response as a demand-side flexibility option to mitigate variability in the energy system in Finland in 2030. The results show that heating loads can provide a significant long-term technical potential for demand-side resource capacity. This demand-side resource capacity is not always available, as it varies according to the season and time of the day. The temporal availability of demand-side resource capacities varies between 80–5600 MW. Furthermore, the results show that the utilisation of demand-side resource capacity decreases significantly when the shifting time interval becomes more constrained. The utilisation of demand-side resource capacity results in balancing of residual demand in the day-ahead market, and thus more efficient utilisation of wind power generation in the Finnish power market. This smoothing effect reduces operating hours of thermal power production and the need for cross-border balancing by electricity imports during the peak hours. According to the sensitivity analysis, the ramping occurrences of district heating CHP units increase significantly with increased share of inflexible baseload nuclear power, while some of the efficiency gains can leak to the neighbouring countries.

Keywords:

Demand response, Shiftable demand, Energy system analysis, Variable renewable energy sources, Power system flexibility, Wind power integration.

1 Introduction

1.1 Background

Electricity and heat generation from renewable energy sources has increased substantially during the past few years in the European Union (EU). Motivation to shift towards low-carbon, renewable-based energy mix has been driven by the concerns regarding the impacts of highly fossil-based energy use trend on the physical, economic, and political environments. Especially, by the increased concern regarding climate change resulting from the increased greenhouse gas (GHG) emissions in atmosphere [1]. The European Commission (EC) has set a target to reduce GHG emissions by at least 40% below the 1990 level by 2030 [2]. In this respect, the European Commission has proposed a target to increase the share of renewable energy to at least 27% of the final energy consumption by 2030. EU member states have outlined National Renewable Energy Action Plans (NREAPs) for advancing the integration of different renewable energy sources. NREAPs project ambitious national targets for increasing variable renewable energy (VRE) integration within electricity markets in particular [3].

Thus far the rapid growth, and plans for further deployment, of wind power capacity has mainly been driven by national energy and climate policies (i.e. feed-in tariffs, quota systems, green certificates, subsidies and other cost incentives) instead of market-driven logic [4]. For instance, in the EU, the share of wind power has increased from 2.1% in 2005 to 9.3% of total gross electricity generation in 2015 [5]. In Finland, the deployment of wind power capacity has been slightly slower. The share of wind power in Finland has increased from 2.4% in 2005 to 3.4% of total gross electricity generation in 2015 [5]. In recent years, renewable energy technologies have experienced significant cost reductions [6]. Furthermore, promoting wind power has been a key ingredient of the Finnish Governments energy and climate policy to increase the share of renewable electricity and decarbonise the energy mix. The Finnish Government prepared the National Energy and Climate Strategy in 2013 [7], which included commitment through feed-in tariff programs to increase its wind power generation to 6 TWh by 2020, and a strategic goal of 9 TWh wind power by 2025. The strategy of 2013 also included a large amount of nuclear power. In addition to the Olkiluoto 3 reactor under construction, the strategy included two new nuclear reactors, Olkiluoto 4 and Hanhikivi 1, which both had earlier received a positive decision-in-principle from the Finnish parliament [8]. In 2016, the National Energy and Climate Strategy was updated, with the main focus in 2030 [9]. The updated strategy included only a modest increase in nuclear power, as the permit of Olkiluoto 4 had expired due to the unwillingness of the licence holder TVO to advance the project in the current power market circumstances. In both of these strategies, it remains a vital issue whether the energy system can be operated efficiently and reliably in the presence of large amounts of both inflexible nuclear power and variable wind power.

Previous research has shown that increasing VRE integration within the electricity markets may cause technical and market related challenges [10–14]. These are inherent with variable renewable resources such as wind power generation, which can experience substantial spatial and temporal variation and is therefore only partially forecastable. This can add more variability and uncertainty to the energy system, which has a potential impact on system reliability and efficiency. For instance, in studies of VRE integration in European countries, it was found that the requirements for demand-supply balancing and reserves increase when the share of electricity generated by wind power in the electricity system exceeds 10-30% of total gross electricity generation [11,15]. Demand-side interventions (e.g. demand response) as a flexibility option have gained more interest in the national energy policy decision-making. EU does not have a specific target for demand response, however its central role in facilitating the integration of VRE can be seen in the recent efforts towards deployment of smart metering technologies and electricity market liberalisation in the EU [16,17].

The research presented in this paper aims to assess the technical effectiveness of demand response as a demand-side flexibility option to mitigate variability in the energy system in Finland in 2030. This paper is a continuation to the research of Olkkonen et al. [18] where demand response was assessed in the Finnish energy system. In this study, Monte Carlo simulations are used to generate stochastically varying time series for the aggregate power generation of multiple wind power generation units taking into account the geographical distribution of the units in the future as presented in the National Energy and Climate Strategies prepared by the Finnish Government. The temporal availability and long-term development of demand-side resource capacity is estimated in the residential and services sectors. The utilisation of end-user demand-side resource capacity is simulated with developed demand response algorithm, which is based on the hourly residual demand variations during the day. This results in balancing of the residual demand in the day-ahead market, and thus better utilisation of the merit-order effect. The effects of demand response on the supply-side are analysed at the energy system level on an hourly basis. The dispatch of the Finnish energy system is simulated in future scenarios with large amounts of baseload nuclear power and variable wind power generation using the EnergyPLAN model.

1.2 Previous research

The short-term marginal cost of production can vary significantly in the day-ahead electricity market according to the time of day. This implies that the true cost of consuming electricity varies also in hour-by-hour basis. Therefore, giving the end-use consumers price signals that reflect the opportunity cost of electricity use could incentivise the demand-side to optimally manage their demand-side resources [19–21]. Previous research has identified demand-side resource capacities in a broad range of processes and devices throughout different sectors and countries [22–26]. For instance, Nyholm et al. [25] estimated the demand response potential of electrical space heating in Swedish single-family dwellings using a dynamic and detailed building-stock model. Similar demand-side resource applications were studied in a model-based long-term scenario analysis in the UK in 2050 [26]. Gils [22] estimated the theoretical demand response potential for European countries. This potential was found to vary strongly between different demand-side resource applications and countries. In regions where seasonal energy demand for heating can be high, electricity demand for heating can offer significant demand-side resource capacity for demand response [27].

Previous research has illustrated that the benefits of utilising these demand-side resources for mitigating variability in the energy system can emerge at both economic and operational levels. For instance, this potential can materialise in terms of reduced system costs of energy supply, increase in system reliability and stability, as well as reduced environmental impacts due to a possible change in marginal energy generation. Utilising demand response can affect the unit commitment and dispatch in the day-ahead electricity market. This can have a significant downward impact on the average electricity spot prices [28] and price variability [29]. However, some studies have found that the system benefits of demand response providing reserves can be more significant than the benefits of demand response on the electricity spot price [29,30]. This is because high variation in VRE generation can cause other production units in the energy system to change generation levels. Consequently, this can lead to the allocation and use of extra reserves [10] and higher requirements for more flexible generation [11]. A number of studies have identified that the utilisation of demand response can result in balancing of renewable energy induced short-term variability in the system [23,31,32], and thus it can facilitate higher integration of VRE into the energy system [33]. Meibom et al. [24] studied the consequences of introducing heat pumps or electric boilers in three district heating systems in the North European power system. The authors conclude that the introduction of heat pumps or electric boilers was found to be beneficial for the integration of wind power in terms of reduced curtailment of wind generation and the price of regulating power, as well as fuel savings in district heating generation. Furthermore, the balancing of residual demand can reduce the need for peak production capacity [32,34], as the utilisation rate of base- and mid-load power plants can increase [23]. Consequently, the environmental effects on the energy system from shifting demand from peak to off-peak hours can depend on the generation mix and interconnections between different power systems [35–37]. Utilisation of demand response can also have long-term effects on the energy system. For instance, Smith and Brown [38] studied the effects of demand response on the long-term capacity expansions using a computational general equilibrium model. The authors conclude that demand response can defer large amounts of peak capacity construction.

The previously mentioned studies illustrate that the effects of demand response on the operation and planning of the power system have been studied extensively using various demand response modelling methods. Research presented in this paper adds to the literature on modelling and analysing the detailed hour-by-hour effects of demand response on the energy system operation, with further taking into account the variability of wind power generation and the temporal availability of demand-side resource applications. This research could give new insights for variable renewable integration by demand response, which would also be relevant for other countries.

2 Methods and materials

To simulate the effects of demand response on the energy system operation in Finland in 2030, a demand response model is developed, which is soft-linked to the existing energy system model EnergyPLAN. Moreover, a wind power model is used to simulate the future wind power scenarios in Finland in 2030. The link between different models is illustrated in Fig. 1.

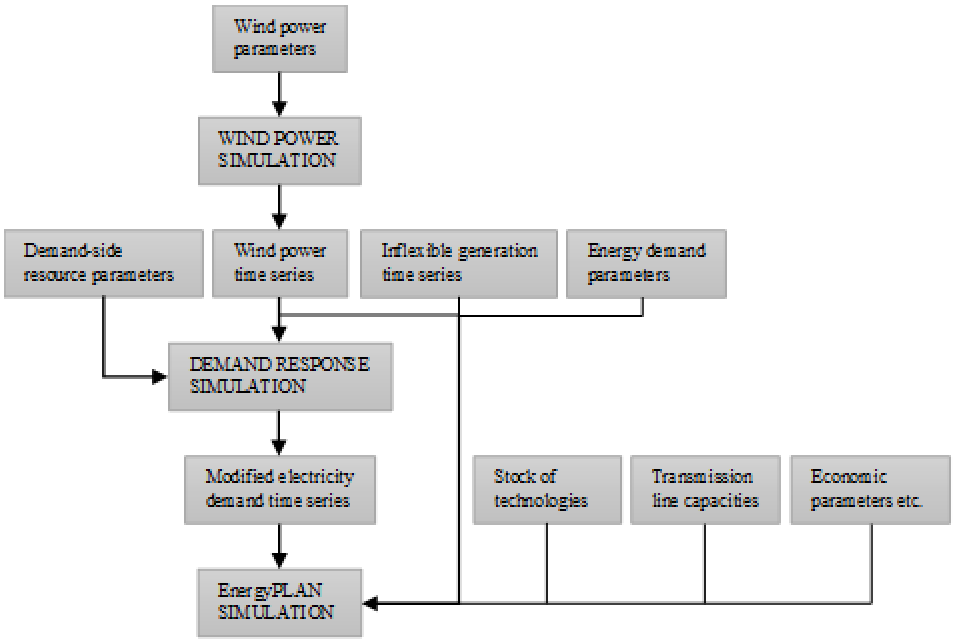

Fig. 1. Soft-link between wind power, demand response and energy system models.

2.1 Modelling of demand response

2.1.1 Estimation of available demand-side resource capacity

In a cold climate region where seasonal energy demand for heating can be high, electricity demand for heating can offer significant demand-side resource for demand shifting. In Finland for example, historically 18–20% of the annual electricity demand is used for heating according to the official statistics of Finland from 2008 to 2016 [39]. In this regard, mainly heating loads are considered in this study for the available demand-side resource capacity. The demand-side resource applications considered are space heating (incl. heat pumps) and hot water storage in the residential and services sectors.

The energy demand of space heating is strongly dependent on the outside temperature. Thus, the hourly demand profile is estimated using the hourly heating degree days[1] (HDD) method and temperature data for 2014 from 16 different cities[2] in Finland [41,42]. The hourly energy demand of space heating ($Q_{SH,h}$) is assumed to be directly proportional to the hourly HDD ($n_{HDD,h}$), as presented in equation (1)

$$Q_{SH,h} = \frac{n_{HDD,h}}{\sum_{h=1}^{8760} n_{HDD,h}} \cdot Q_{SH,a} \tag{1}$$

In (1) $Q_{SH,a}$ represents the annual heat demand of space heating, found in the statistics [9,39,43]. The electricity use of heat pumps is estimated using the previously described method, with further taking into account the temperature dependent heat pump coefficient of performance (COP).

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[1] The base temperature used by the Finnish Meteorological Institute is 17 °C [40].

[2] Selection of reference cities for the hourly HDD estimation follows the method used by the Finnish Meteorological Institute [40]. However, since the temperature differences between selected cities can be very significant, weighting method based on residential and services electricity demand is used when calculating the hourly average temperature.

The hourly energy demand of hot water storage in the residential and services sectors is estimated using the equations (2) and (3)

$$Q_{HWS,d} = \frac{\left(\frac{Q_{HWS,a}}{12} q_{HWS,m}\right)}{n_{d,m}} q_{HWS,d} \tag{2}$$

$$Q_{HWS,h} = \frac{d_{HWS,h}}{\sum_{h=1}^{24} d_{HWS,h}} Q_{HWS,d} \tag{3}$$

Equation (2) represents the average daily energy demand of hot water storage ($Q_{HWS,d}$) in the month m. In (2) $Q_{HWS,a}$ represents the annual heat demand of hot water storage, found in the statistics [9,39,43], and $n_{d,m}$ represents the number of days in the month m. Furthermore, in (2) the average daily energy demand of hot water storage is estimated using the daily ($q_{HWS,d}$) and monthly ($q_{HWS,m}$) correction factors that account for the daily (weekday/weekend) and seasonal influence on the hot water consumption, as presented in [44]. Equation (3) represents the hourly energy demand of hot water storage ($Q_{HWS,h}$). In (3) the average daily energy demand of hot water storage is assumed to be directly proportional to the hot water consumption profile ($d_{HWS,h}$). The hourly energy demand of residential hot water storage is estimated using the average daily hot water consumption profile for Finland, as presented in [45]. Furthermore, the hourly energy demand of hot water storage in the services sector is estimated using the average daily hot water load profiles of non-residential buildings (incl. office buildings, educational buildings, hospitals, restaurants and hotels), as presented in [46].

The temporal availability of demand-side resource capacity varies between 80–5600 MW in Finland in 2030, as presented in Fig. 2. For comparison [22], estimate an average theoretical demand reduction potential of 5400 MW in Finland for the comparable demand-side resource applications based on 2010 data.

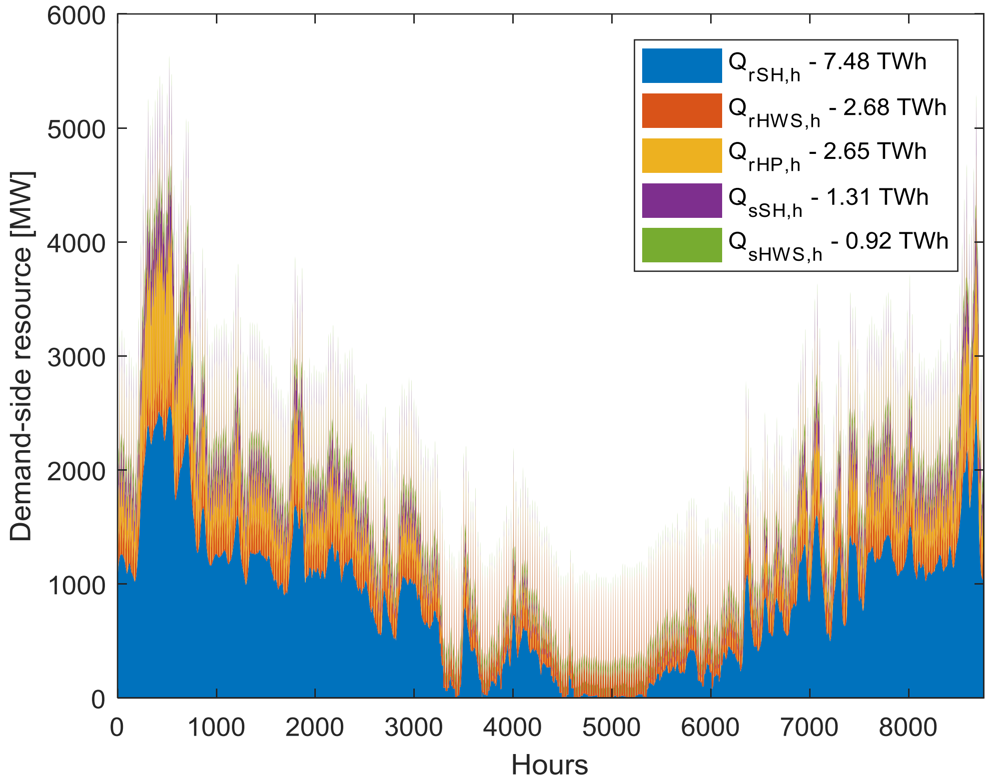

Fig. 2. Temporal availability of estimated demand-side resource capacity in Finland in 2030: residential space heating ($Q_{rSH,h}$), residential hot water storage ($Q_{rHWS,h}$), residential heat pump ($Q_{rHP,h}$), services space heating ($Q_{sSH,h}$) and services hot water storage ($Q_{sHWS,h}$). The annual electricity demand is displayed next to the corresponding demand-side resource application.

2.1.2 Demand response model

The hourly utilisation of end-user demand-side resource capacities is based on the hourly variations in residual electricity demand[3], and it is simulated with a MATLAB based algorithm. Residual demand is used as an objective variable since the scope of the study is to assess the technical effectiveness of demand response as a demand-side flexibility option to mitigate variability in the energy system. This approach is in accordance with the findings in [29,30], which suggest that the system benefits of demand response providing reserves can be more significant than the system benefits on the spot price. Moreover, due to the renewable energy induced merit-order effect[4], there is often a negative correlation between renewable energy generation and the electricity spot price [14,48]. The hourly utilisation of end-user demand-side resource capacities is simulated in an iterative process over simulation time horizon of a year. The following procedure is applied for the demand response modelling in each day:

- The hour where demand is reduced is determined by the hour with the highest residual demand (t_{From}), and it is subject to constraint (4). Furthermore, the demand-side resource applications are modelled as shiftable demand, which is subject to constraints presented in (5) and (6)

$$d_{j,t}^{dsr} > 0 \tag{4}$$

$$\sum_{t \in D}^{t+t_j^{shift}} d_{j,t}^{shift} = 0 \tag{5}$$

$$\sum_{t \in D} d_{j,t}^{shift} = 0 \tag{6}$$

  Constraint (4) imposes the requirement that the available demand-side resource capacity of demand-side resource application j ($d_{j,t}^{dsr}$) in the hour where demand is reduced (t_{From}) is greater than zero. Constraints (5) and (6) impose the requirements that equivalent of reduced demand must be recovered within the shifting time interval (t_j^{shift}) (5) and within a day (6). In (5) and (6), shiftable demand ($d_{j,t}^{shift}$) is negative for demand reduction and positive for demand recovery. This modelling approach for the considered demand-side resource applications is based on the definitions from [22] for heating loads.

- The hour where demand is recovered is determined by the hour with the lowest residual demand (t_{To}), and it is subject to constraints presented in (7)–(9)

$$Q_{j,t} < Q_{j,max} \tag{7}$$

$$t_{To} < t_{From} \tag{8}$$

$$|t_{From} - t_{To}| \leq t_j^{shift} \tag{9}$$

  Constraint (7) imposes the requirement that the current electricity demand of demand-side resource application j ($Q_{j,t}$) in the hour where demand is recovered (t_{To}) is lower than the maximum electricity demand of demand-side resource application j ($Q_{j,max}$) during the simulated year. Constraint (8) imposes the requirement that the demand-side resource capacity can only be advanced. This constraint is based on the assumption that heating load can be shifted to an earlier time in the day to enable preheating. The maximum duration until the reduced demand must be recovered is restricted by the shifting time interval (t_j^{shift}), as presented in constraint (9). Shifting time interval, specific to demand-side resource application

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[3] Residual demand is the portion of the electricity demand that is not met by the energy generation from the inflexible sources. Since the demand response algorithm is soft-linked to the EnergyPLAN, same definition of the inflexible sources is used in the demand response simulation.

[4] Renewable energy is often subjected to very low or even negative short-term marginal cost of production if renewable support schemes are taken into account [47]. Renewable generation is therefore often prioritised and fed into the market first. Consequently, renewable energy offers are located on the left part of the supply curve, thus replacing technologies with higher short-term marginal cost of production. This so-called merit-order effect can result in a lower electricity spot price.

j, is based on the estimates of the average demand shifting time frames from [22,25] and are constrained by the physical storage capacities and/or the thermal capacity of building structures. Shifting time interval for space heating and hot water storage is estimated to be up to 12 hours, and up to 2 hours for heat pumps.

- The amount of demand that can be shifted from the hour where demand is reduced (t_{From}) to the hour where demand is recovered (t_{To}) is subject to constraint (10)

$$d_{j,t}^{shift} \leq \begin{cases} d_{j,t}^{dsr} & if \ d_{j,t}^{dsr} \leq \frac{\left|d_{t_{From}}^{res} - d_{t_{To}}^{res}\right|}{2} \\ \frac{\left|d_{t_{From}}^{res} - d_{t_{To}}^{res}\right|}{2} & if \ d_{j,t}^{dsr} > \frac{\left|d_{t_{From}}^{res} - d_{t_{To}}^{res}\right|}{2} \\ 0 & if \left|d_{t_{From}}^{res} - d_{t_{To}}^{res}\right| = 0 \\ Q_{j,max} - Q_{j,t} & if \ d_{j,t}^{dsr} + Q_{j,t} > Q_{j,max} \end{cases} \tag{10}$$

Constraint (10) imposes three requirements for the shiftable demand ($d_{j,t}^{shift}$), which are dependent on (i) the availability of demand-side resource capacity ($d_{j,t}^{dsr}$), (ii) the hourly residual electricity demand (d_t^{res}) balance, and (iii) the current electricity demand of demand-side resource application j ($Q_{j,t}$). The lower limit for demand reduction ($d_{j,t}^{shift}$) is determined by the available demand-side resource capacity[5] ($d_{j,t}^{dsr}$) of demand-side resource application j in the hour where demand is reduced (t_{From}). The residual demand (d_t^{res}) in the hour where demand is recovered (t_{To}) cannot exceed the residual demand in the hour where demand is reduced (t_{From}) after the shiftable demand ($d_{j,t}^{shift}$) is shifted. Finally, the electricity demand of demand-side resource application j ($Q_{j,t}$) in the hour where demand is recovered (t_{To}) cannot exceed the maximum electricity demand of demand-side resource application j ($Q_{j,max}$) during the simulated year after the shiftable demand ($d_{j,t}^{shift}$) is shifted. The available demand-side resource capacity ($d_{j,t}^{dsr}$), the electricity demand of demand-side resource application j ($Q_{j,t}$) and the residual electricity demand (d_t^{res}) are dynamic variables, which are updated in each iteration. Moreover, the iteration procedure within a day is continued until a residual demand balance is found or the demand-side resource capacity is fully employed.

The temporal variability in wind power generation is taken into account by producing 100 different temporal outcomes for the wind power generation profile in the wind power simulation. Consequently, an equivalent amount of demand response scenarios are simulated that only differ by the temporal variation in residual demand.

2.2 Modelling of energy system

2.2.1 Energy system model

In order to examine the effects of demand response on the energy system operation in Finland in 2030, the Finnish energy system is simulated with an analytic programming based EnergyPLAN model. EnergyPLAN is a descriptive simulation model, which simulates the dispatch of energy generation resources to meet the energy demand requirements of the system on an hourly basis over the simulation time horizon of a year (t = 1,…, 8784) using aggregated input data on the energy system assets [49,50]. The model simulates the energy system as one node, and thus it does not take into account the internal limits of electricity transmission capacity.

Energy conversion units are categorised into two groups based how they operate in the simulation procedure. Energy generation from nuclear power, industrial backpressure, waste-to-energy, run-of-river hydro power and VRE generation follow the predetermined distribution profiles, and thus, the

[5] The end-use consumers' willingness to shift demand is not considered in this technical potential. Thus, an assumption is made that estimated hourly demand-side resource capacity is fully elastic within the defined shifting time interval.

hourly generation from these units is considered inflexible. Energy generation from the inflexible sources is deducted from the hourly energy demand and the remaining residual demand will be met by the flexible part of the operating stock of technologies. Flexible energy generation units used for balancing are hydro power with storage, district heating combined heat and power (CHP), heat-only boiler, heat pump and other thermal power (i.e. conventional condensing power, peak gas turbines and gas engines). The operation of flexible energy generation units is considered fully elastic[6], i.e. the operating level of flexible energy generation unit in the hour *t* is not restricted by the operating level in the hour *t–1*. The upper limit for district heating CHP electricity generation in cogeneration mode in the hour *t* is determined by the district heating demand (and the thermal storage capacity) in the hour *t*.

The model provides the user different options for regulation strategies used for the modelling and simulation of a given energy system. In this study, the market-economic simulation is used. The model simulates the merit-order dispatch of electricity generation units, assuming that the energy markets are perfectly competitive and have perfect foresight. The short-term marginal cost of production is determined for each technology type using technology and economic data and the least-cost combination of flexible energy conversion units is assigned to supply the residual energy demand in each hour. External electricity market is described in the model as one node, which has the properties of net transmission capacity, system price and price elasticity parameter. The price of electricity on the external market is determined as a function of electricity net import. Importing electricity from the external market will increase the price of electricity on the external market. The balance on cross-border flow of electricity is found in an iterative procedure, which continues until the short-term marginal cost of production in the power system would be equal to the external market, or the net transmission capacity is fully employed, resulting in bottleneck.

2.2.2 Wind power model

A validated statistical methodology is used to generate synthetic wind power time series for the 2030 scenarios. The variability of wind generation is modelled with a statistical methodology consisting of probability integral transformations and time series modelling with autoregressive model. The methodology is utilised to generate synthetic multivariate wind speed time series, with hourly time resolution, for each individual wind farm (or turbine) using Monte Carlo simulations. The wind speed time series are transformed to wind power time series with a wind turbine model according to the specifications of each individual turbine or wind farm. The obtained wind power time series for each generation location are then combined to aggregated wind power time series for the whole wind generation in the system. Similar modelling approach has been utilised in [51] and [52].

The general simulation setup used to simulate the future 2030 scenarios is based on the model presented for Finland in [51]. In this study, the model is updated according to the actual installed wind generation capacity in Finland by January 2016 consisting of 377 turbines. The complete generation structure including all individual turbines is considered in the simulation setup and the geographical distribution of the turbines is also taken into account and modelled in detail. The annual wind power generation of about 7–9 TWh scenarios for 2030 are considered as presented in [7,9]. The future scenarios require considerably additional generation capacity to the actual installed capacity of 1005 MW in 2016 [53]. The additional capacity is modelled by expanding the existing wind farms with new turbines according to planned extensions up to the assumed installed capacity of 3000–3700 MW. Furthermore, 100 simulation runs, with the length of one year, are generated to produce 100 different temporal outcomes.

[6] The model does not consider the following parameters that are often used to characterise the operational flexibility of a generation unit: start-up time, minimum up- and downtime or ramping rates of the energy generation unit or costs that are associated with cycling processes.

2.2.3 Description of input data and scenarios

The composition of stock of energy generation technologies in Finland in 2030 and description of energy system scenarios are presented in **Error! Reference source not found.**. Moreover, input data and the assumptions included in different energy system scenarios are the following:

- *Load forecast*: Based on measured hourly demand profile for 2014 [54] and adjusted for the future load expectations as forecasted by [9].
- *Stock of technologies*: Based on data for 2014 [54,55], including heat rates, fuel and technology types, and supplemented with capacity additions mainly to wind and nuclear power as described in the Finnish National Energy and Climate Strategy of 2016 for 2030 [9]. Distribution of inflexible generation is based on measured hourly data for 2014 [54] and adjusted for the future commissioning and decommissioning expectations. Technology cost information, including variable O&M, investment and fixed O&M cost, based on Danish Energy Agency's data [56].
- *Net transmission capacity and electricity price*: Based on ENTSO-E [57] data on projected net transmission capacity investments for 2030 and Nord Pool [58] data on current commercial exchange capacities, including: FI/SE 2700 MW, FI/EE 1016 MW, FI/NO 90 MW and FI/RU 1300 MW. Moreover, the net transmission capacity from Northern Sweden (i.e. bidding area SE1) to Finland is projected to increase by 800 MW by the end of 2025. Electricity price distribution on the external electricity market is based on the historical hourly system price profile in Nord Pool market for 2014 [58] and it is adjusted with the forecasted emission and fuel prices. The assumed average spot price is 60 €/MWh as forecasted by [9].
- *Fuel prices and emissions*: Fuel prices are based on the forecast from IEA World Energy Outlook 2015 [59]. Used fuel prices reflect the delivered prices to energy producers, including energy taxes, stock fees and oil pollution fees for energy products, which are assumed to remain constant at the 2016 level [60]. Fuels are divided into four groups; coal (including primary and secondary coal, manufactured gases and peat), oil (crude oil and petroleum products), natural gas (including gas works gas) and biomass (including biofuels and waste). Emissions information is based on the IPCC guidelines for national greenhouse gas inventories [61] and the assumed average emission price is 30 €/tCO_2.

Table 1
Energy system scenarios for Finland in 2030; installed capacities, net transfer capacities, and electricity and heat demands.

Scenario	Electricity demand [TWh]	District heating demand [TWh]	Heat-only boiler [MJ/s]	Wind power [MW]	PV [MW]	Hydro power [MW]	Nuclear power [MW]	Industrial backpressure [MW]	District heating CHP			Other thermal power [MW]	District heating thermal storage [GWh]	Net transfer capacities [MW]
									CHP mode [MW]	Cond. mode [MW]	Thermal [MJ/s]			
EC2016	92	31	13700	3000	10	3026[a]	4560	2567	3966	3300[b]	6559	565	17[c]	5800
HIGH NUCLEAR	-[d]	-	-	-	-	-	6160	-	-	-	-	-	-	
HIGH NUCLEAR/ HIGH VRE	-	-	-	3690	-	-	6160	-	-	-	-	-	-	

Scenario	Description
EC2016	Scenario assumptions corresponds to the assumptions in presented in the Finnish National Energy and Climate Strategy of 2016 [9]. Nuclear power capacity is projected increase by the units currently under construction or planning, which include Olkiluoto 3 (1600 MW) reactor and Hanhikivi 1 (1200 MW) reactor. Loviisa 1 (498 MW) reactor and Loviisa 2 (500 MW) reactor are assumed to be decommissioned by the end of 2030. The annual wind power generation of about 7 TWh (7.6% of the total gross consumption) for 2030 is assumed.
EC2016/ LIMITED EXCHANGE	The same operating stock of technologies as in EC2016. In LIMITED EXCHANGE scenario, the electricity transmission opportunities to the external market are limited to the critical balancing situations only where the electricity demand exceeds the available electricity generation capacity or the electricity generation from inflexible sources exceeds the electricity demand.
EC2016/ DEMAND PROGNOSIS	The same operating stock of technologies as in EC2016. In DEMAND PROGNOSIS scenario, demand response is modelled with electricity demand prognosis time-series. Thus, the scenario describes the effect of short-term forecast errors of electricity demand in the day-ahead market.
HIGH NUCLEAR	The same operating stock of technologies as in EC2016, but additions to the nuclear power capacity as presented in the Finnish Energy and Climate Strategy of 2013 [7]. The HIGH NUCLEAR scenario includes the construction of three new nuclear power units Olkiluoto 3, Hanhikivi 1 and Olkiluoto 4 (1600 MW).
HIGH NUCLEAR/ HIGH VRE	The same operating stock of technologies as in HIGH NUCLEAR, but additions to the wind power capacity as presented in the Finnish Energy and Climate Strategy of 2013 [7]. The annual wind power generation of about 9 TWh (9.8% of the total gross consumption) for 2030 is assumed.
HIGH NUCLEAR/ HIGH VRE/ LIMITED EXCHANGE	The same operating stock of technologies as in HIGH NUCLEAR/HIGH VRE. In LIMITED EXCHANGE scenario, the electricity transmission opportunities to the external market are limited to the aforementioned critical balancing situations only.

[a] Installed capacity of hydro power includes both run-off-river hydro and hydro power witch storage capacities.

[b] Installed capacity of district heating CHP in condensing mode is estimated from historical data [54].

[c] Heat conversion units are assumed to be able to optimise thermal storage capacity to cover the heat load for a maximum of seven days [56].

[d] Empty cell in the table depicts no change in installed capacity compared to the Energy and Climate Strategy of 2016 scenario (EC2016).

3 Results and discussion

3.1 The effect of demand response on the energy system operation and required power plant ramping

The effect of demand response on the energy system operation, i.e. change in production of different technologies and electricity exchange, is determined by the magnitude and temporal placement of the demand response occurrence. Due to the necessity of demand-supply balance in the energy system, the ramping occurrences in the supply-side follow the direction of the demand response occurrences. Therefore, higher frequency of production ramp-down occurrences can be observed during the peak[7] demand hours when the frequency of demand reduction occurrences is higher. On the contrary, higher frequency of production ramp-up occurrences can be observed during the off-peak 1 hours when shifted demand is recovered.

Moreover, in the energy-only[8] power market, the electricity supply curve is constructed based on the merit-order principle, according to which supply offers are arranged depending on their short-term marginal cost of production [63]. In this context, the slope of the supply curve describes the operating stock of electricity generating technologies that are dispatched in the merit order to meet the residual demand. Therefore, the affected electricity generation unit on the slope of the supply curve is the one committed with the highest short-term marginal cost of production during the hour of demand reduction/recovery occurrence. Moreover, the affected unit(s) can comprise several electricity generation technologies depending on the slope of the supply curve and the magnitude of the demand response occurrence [64].

The effect of demand response on the energy system operation in Finland in 2030 in the simulated scenarios is summarised in Table 2. In all scenarios, the utilisation of demand response has the most significant impact on the thermal power production and electricity exchange. The effect of residual demand uncertainty is highlighted in EC2016/DEMAND PROGNOSIS. The results presented in Table 2 (and Table A. 1 Appendix A) show that the changes in production of different technologies and electricity exchange due to demand response are generally lower when the residual demand uncertainty is taken into account. This is because the differences between forecasted and measured electricity demand lead to less optimal utilisation of demand-side resource capacity.

As presented in Table 3, thermal power production and electricity imports decrease during the peak hours when demand is reduced. This illustrates that demand reduction during the peak hours (i) substitutes the peak production capacity and (ii) leads to reduced need for cross-border balancing by electricity imports. Furthermore, the magnitude of thermal power and import ramping occurrences can experience significant temporal variation during the day. This is illustrated in Fig. 3. Notably, largest reductions in electricity imports can be observed during the months from January to April when the residual demand is generally higher during the year. Conversely, an increase in electricity exports can be observed during the peak hours. This is due to the balancing of hourly district heating demand and supply. In some cases, the electricity price on the external market is high enough that the CHP heat conversion can still be more profitable than meeting the heat demand by using a heat-only boiler. Thus, the district heating CHP unit is kept online to meet the district heating demand and the excess electricity production is exported to the external market. Higher share of inflexible baseload capacity in HIGH NUCLEAR (and HIGH NUCLEAR/HIGH VRE) increases significantly the number of excess production hours, as presented in Table A. 2 (Appendix A). This result could be interpreted as a negative effect that the utilisation of demand response can have on the system efficiency. However, this result is affected by the consequences that exported electricity has on the external market (Nord Pool power market). For instance, the overall effect of demand response on

[7] In the Nord Pool power market, the off-peak and peak hours are defined as follows: off-peak 1 from midnight (00:00) to 8 a.m. (8:00), peak from 8 a.m. (8:00) to 8 p.m. (20:00) and off-peak 2 from 8 p.m. (20:00) to midnight (24:00) [62].

[8] Energy-only market is a type of market design where producers are remunerated for their energy but not their available capacity or reliability services.

the system efficiency could be net-positive in the case where exported excess electricity production from a district heating CHP plant can avoid the start-up or ramp-up of a thermal power unit in the external market.

Hydro power production does not change in annual terms. However, the hydro producers attempt to maximise their profits by allocating more production to the off-peak 1 hours where the shifted demand is recovered. This is illustrated in Table 3. Furthermore, demand recovery during the off-peak 1 hours leads to higher utilisation of excess production in the internal market, and thus a decrease in electricity exports can be observed. On the contrary, electricity imports increase during the off-peak 1 hours. This is due to lower short-term marginal cost of production on the external market (Nord Pool power market), which makes importing electricity from the external market more profitable. The effect of the composition of operating stock of technologies on the electricity exchange is highlighted in HIGH NUCLEAR (and HIGH NUCLEAR/HIGH VRE).

Table 2
Summary of the changes in annual production of different technologies and electricity exchange due to demand response in Finland in 2030 in different scenarios. Annual results are presented as mean, minimum and maximum values of the 100 simulations.

		Change in annual production of different technologies and electricity exchange due to demand response [GWh]		
		MEAN	MIN	MAX
EC2016	Thermal power	-552	-648	-473
	District heating CHP	-4	-16	11
	Import	362	245	439
	Export	-194	-241	-150
EC2016/LIMITED EXCHANGE	Thermal power	103	20	169
	District heating CHP	-2	-44	58
	Critical import	-140	-188	-87
	Critical export	-39	-61	-19
EC2016/DEMAND PROGNOSIS	Thermal power	-549	-645	-469
	District heating CHP	-3	-14	11
	Import	359	253	437
	Export	-194	-246	-148
HIGH NUCLEAR	Thermal power	-98	-129	-73
	District heating CHP	57	-2	131
	Import	-144	-217	-58
	Export	-184	-269	-104
HIGH NUCLEAR/HIGH VRE	Thermal power	-74	-104	-36
	District heating CHP	9	-66	99
	Import	-144	-219	-85
	Export	-210	-313	-87
HIGH NUCLEAR/HIGH VRE/LIMITED EXCHANGE	Thermal power	-15	-57	30
	District heating CHP	-629	-766	-525
	Critical import	-29	-50	-10
	Critical export	-485	-580	-394

Higher share of baseload nuclear power (and wind power) capacity lowers the short-term marginal cost of production in the internal market (Finnish power market)[9]. This leads to significantly reduced need for cross-border balancing by electricity imports. Therefore, the change in electricity imports due to demand response is also lower in the aforementioned scenarios. The reader should note that the external electricity market is described as one node in the EnergyPLAN model, which has the properties of net transmission capacity, system price and price elasticity parameter. Thus, electricity flows between different bidding areas that are induced by the possible area price differences are not captured realistically by the model. Moreover, in the future, higher integration of VRE electricity generation into the Nordic market area, and further integration of Nordic market area to Western European market, may have a considerable impact on the annual average system price [65] and price differences between bidding areas and hourly price volatility [48]. For instance, in the future scenarios there could be more hours of excess VRE electricity generation in the Nordic market since wind power generation can coincide over large areas [66]. This is not captured in the Nord Pool electricity price data used in the modelling. Therefore, the effect of utilising demand response on the electricity exchange could be even higher. In this case, a market participant that utilises demand response could take even more advantage of the excess VRE generation from its neighbouring countries in terms of cheaper electricity imports. This can reduce the operating hours of thermal power even further to what was observed in the simulated scenarios. Consequently, this can reduce the supply-side flexibility in the long-term since the profitability of thermal power is reduced [18], which can affect the future investments decisions.

Table 3
Seasonal and diurnal change in production of different technologies and electricity exchange due to demand response in Finland in 2030 in EC2016 scenario. Averaged annual results of 100 simulations are divided between seasons and time of the day: Off-peak 1 hours (1:00 to 8:00), Peak hours (9:00 to 20:00) and Off-peak 2 hours (21:00 to 24:00).

		Change in production of different technologies and electricity exchange due to demand response [GWh]		
Jan. to Apr.		Off-peak 1	Peak	Off-peak 2
	Thermal power	44	-72	-9
	District heating CHP	17	-15	-2
	Hydro power	157	-113	-34
	Import	431	-407	-59
	Export	-78	15	2
May to Aug.		Off-peak 1	Peak	Off-peak 2
	Thermal power	-1	-135	0
	District heating CHP	48	-48	-4
	Hydro power	12	-165	-16
	Import	384	-141	-19
	Export	-79	-8	3
Sept. to Dec.		Off-peak 1	Peak	Off-peak 2
	Thermal power	-3	-353	-25
	District heating CHP	20	-19	-1
	Hydro power	249	-68	-22
	Import	504	-283	-47
	Export	-61	13	0

[9] In HIGH NUCLEAR (HIGH NUCLEAR/HIGH VRE), increasing nuclear power (and wind power) capacity result in right-shift of the slope of the supply curve. This is due to lower short-term marginal cost of nuclear power (and wind power) production. Consequently, the demand curve intersects the supply curve at a lower short-term marginal cost production.

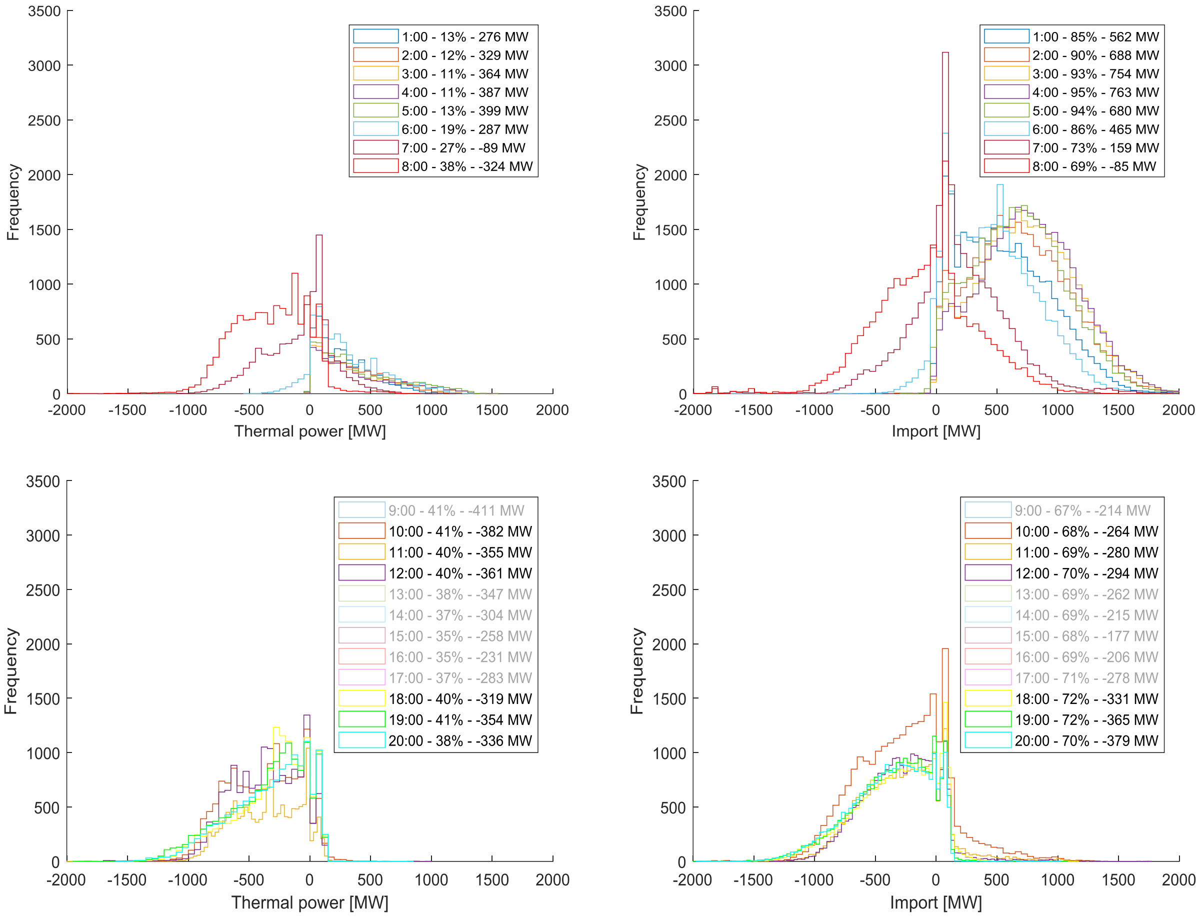

Fig. 3. Histogram of thermal power and import ramping occurrences during the off-peak 1 and peak hours in Finland in 2030 in EC2016 scenario. The off-peak 1 hours from 1:00 to 8:00 and peak hours from 9:00 to 20:00 are depicted by different colours. Only ramping occurrences during peak demand hours from 10:00 to 12:00 and 18:00 to 20:00 are visible in the histogram. Relative frequency and average magnitude of a ramping occurrence are displayed next to the corresponding hour in the legend. Relative frequency depicts the amount of non-zero ramping occurrences in relation to the total amount of the occurrences in the 100 simulation runs.

3.2 The effect of demand response on the capacity scarcity and surplus hours

The effect of demand response on the scarcity and surplus hours[10] is highlighted in the scenarios EC2016/LIMITED EXCHANGE and HIGH NUCLEAR/HIGH VRE/LIMITED EXCHANGE. As presented in Table A. 1 and Table A. 3 (Appendix A), demand reduction during the peak hours reduces significantly the number of capacity scarcity hours (critical import). Notably, largest reductions in critical electricity imports can be observed during the months from September to April when the residual demand is generally higher during the year. Conversely, demand recovery during the off-peak 1 hours reduces the number of capacity surplus hours (critical export). Utilisation of demand response can therefore reduce the need for wind power curtailment[11] during the hours when transmission capacity is limited. This effect becomes more significant when the share of inflexible baseload capacity increases, as highlighted in HIGH NUCLEAR/HIGH VRE/LIMITED EXCHANGE. Surplus hours occur mostly during the months from May to August when the residual demand is generally lower.

[10] Scarcity and surplus hours describe the situations where the electricity demand exceeds the available electricity generation capacity, and vice versa, where electricity generation from inflexible sources exceeds the electricity demand.

[11] Curtailment is a method of regulating substantial amounts of VRE production in power systems.

3.3 The effect of demand response on the demand profile

The utilisation of demand response in Finland in 2030 in the simulated scenarios is summarised in Table 4. The utilisation of demand response has a similar pattern in all simulated scenarios. This is because the residual demand variation did not change significantly between the simulated scenarios. Furthermore, the available demand-side resource capacity was not fully employed in any of the simulated scenarios.

As illustrated in Table 4, the utilisation of demand response can have significant seasonal variation. This is mostly driven by the higher variation in outside temperature, and consequently higher variation in residual demand during the months from September to April. Furthermore, the availability of demand-side resource capacity is also higher during the months from September to April, as presented in Fig. 1. This is because the electricity demand of demand-side resource applications is also for the most part strongly dependent on the outside temperature and/or time of the day. This leads to higher utilisation of available demand-side resource capacity during the months from September to April. This situation is reversed during the months from May to August. Thus, the utilisation of demand response and the magnitude of demand reduction/recovery occurrences are significantly lower during the months from May to August.

Table 4
Seasonal and diurnal changes in demand response utilisation in Finland in 2030 in different scenarios. Averaged annual results of 100 simulations are divided between seasons and time of the day: Off-peak 1 hours (1:00 to 8:00), Peak hours (9:00 to 20:00) and Off-peak 2 hours (21:00 to 24:00).

		Demand reduction [GWh]			Demand recovery [GWh]		
Jan. to Apr.		Off-peak 1	Peak	Off-peak 2	Off-peak 1	Peak	Off-peak 2
	EC2016	-57	-651	-107	784	30	1
	EC2016/DEMAND PROGNOSIS	-61	-569	-111	697	43	1
	HIGH NUCLEAR	-57	-652	-108	786	30	1
	HIGH NUCLEAR/HIGH VRE	-58	-574	-163	732	62	1
May to Aug.		Off-peak 1	Peak	Off-peak 2	Off-peak 1	Peak	Off-peak 2
	EC2016	-49	-489	-44	572	9	1
	EC2016/DEMAND PROGNOSIS	-46	-489	-40	565	9	0
	HIGH NUCLEAR	-49	-488	-44	571	9	1
	HIGH NUCLEAR/HIGH VRE	-38	-449	-73	541	17	3
Sept. to Dec.		Off-peak 1	Peak	Off-peak 2	Off-peak 1	Peak	Off-peak 2
	EC2016	-61	-755	-97	893	19	1
	EC2016/DEMAND PROGNOSIS	-51	-739	-110	877	23	1
	HIGH NUCLEAR	-63	-760	-95	897	20	1
	HIGH NUCLEAR/HIGH VRE	-60	-730	-134	881	41	1

As presented in Table 4, demand is reduced during the peak hours when the residual demand is generally higher, and vice versa, shifted demand is recovered during the off-peak 1 hours when the residual demand is generally lower in Finland. The temporal variation in demand response occurrences during the day is illustrated in Fig. 4. Notable is that the simulated demand reduction/recovery occurrences are not always symmetrically distributed and the occurrences can have large variation in magnitude depending on the hour. The utilisation of available demand-side resource capacity is significantly lower during the off-peak 2 hours. This results from the technical limitations caused by the characteristics of demand-side resource applications. Heating loads are described as shiftable demand that can only be advanced. In Fig. 4, this effect can be observed as skewness in the distribution of demand response occurrences, especially during the off-peak 2 hours. Furthermore, this illustrates the sensitivity that the characteristics of demand-side resource applications have on its effectiveness to mitigate variability in the system during the day.

As illustrated in Fig. 4, demand recovery during the off-peak 1 hours can be high in magnitude when the residual demand variation during the day is high. This can lead to a formation of new demand peaks during the day, as illustrated in Fig. 5. This is in accordance with the findings presented in [18], [29]. The formation of new demand peaks during the day can be expected when the demand-side flexibility option is shiftable demand and the consumers are a homogenous[12] group. The magnitude of new demand peaks was slightly higher in the scenarios HIGH NUCLEAR/HIGH VRE and EC2016/DEMAND PROGNOSIS. In HIGH NUCLEAR/HIGH VRE, this is a result of higher residual demand variation during the day induced by increased wind power capacity. In EC2016/DEMAND PROGNOSIS, this is a result of over shifting demand during the day caused by the differences between forecasted and measured electricity demand. Furthermore, the utilisation of demand response reduced the highest peak demand during the simulated year in all simulated scenarios. However, an increase in the highest peak demand during the year can be observed in some demand response scenarios[13].

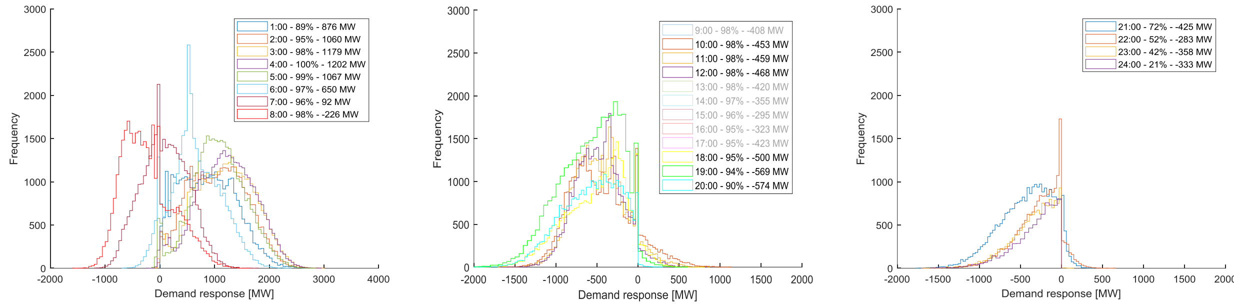

Fig. 4. Histogram of demand response occurrences during the off-peak 1, peak and off-peak 2 hours in Finland in 2030 in EC2016 scenario. The off-peak 1, peak and off-peak 2 hours are depicted by different colours. Only demand response occurrences during the peak hours from 10:00 to 12:00 and 18:00 to 20:00 are visible in the histogram. Relative frequency and average magnitude of a demand response occurrence are displayed next to the corresponding hour in the legend. Relative frequency depicts the amount of non-zero demand response occurrences in relation to the total amount of the occurrences in the 100 simulation runs.

3.4 The effect of shifting time interval on the utilisation of demand response

When the demand-side flexibility option is shiftable demand, as opposed to load shedding[14], the commitment of demand-side resource capacity is also constrained by its shifting time interval. As illustrated in Fig. 4, the duration between the demand response occurrences where the shiftable demand is reduced and recovered can be long. Space heating and hot water storage are characterised with longer maximum duration for the shifting time interval, up to 12 hours, due to the physical storage capacities and/or the thermal capacity of building structures. This enables preheating in earlier time of the day where demand reduced during the peak hours and recovered during the off-peak 1 hours.

In reality, the shifting time interval could be more constrained when the end-users individual preferences (e.g. loss of comfort) are taken into account. The effect of shifting time interval on the utilisation of demand-side resource capacity is simulated in EC2016 scenario. This effect is quantified by gradually decreasing the shifting time interval of space heating and hot water storage. As presented in Table 5, the annual utilisation of demand-side resource capacity decreases when the shifting time

[12] In this case, a large group of consumers whose response to the electricity spot price is identical and have similar patterns of demand reduction/recovery.

[13] Demand response scenarios depict the different temporal outcomes for wind power generation.

[14] Load reduction/shedding is a demand-side flexibility option where demand is purely reducible that does not need to be recovered.

interval becomes more constrained, This is because the shifting time interval describes the time frame where the variations in residual demand can be balanced. When the shifting time interval becomes more constrained, some of the off-peak 1 hours with balancing opportunities become unattainable, as illustrated in Fig. 5. This illustrates that when the demand-side flexibility option is shiftable demand, the shifting time interval of demand-side resource application can be more significant factor for the demand flexibility than the maximum available demand-side resource capacity.

Table 5
The effect of shifting time interval on the annual utilisation of demand-side resource capacity in Finland in 2030 in scenario EC2016.

	Shifting time interval [h]										
	2	3	4	5	6	7	8	9	10	11	12
Annual utilisation of demand-side resource capacity [TWh]	0.29	0.60	0.89	1.25	1.59	1.87	2.04	2.14	2.21	2.26	2.31
Percentage change compared to the 12 hour shifting time scenario [%]	-87 %	-74 %	-62 %	-46 %	-31 %	-19 %	-12 %	-7%	-4 %	-2 %	-

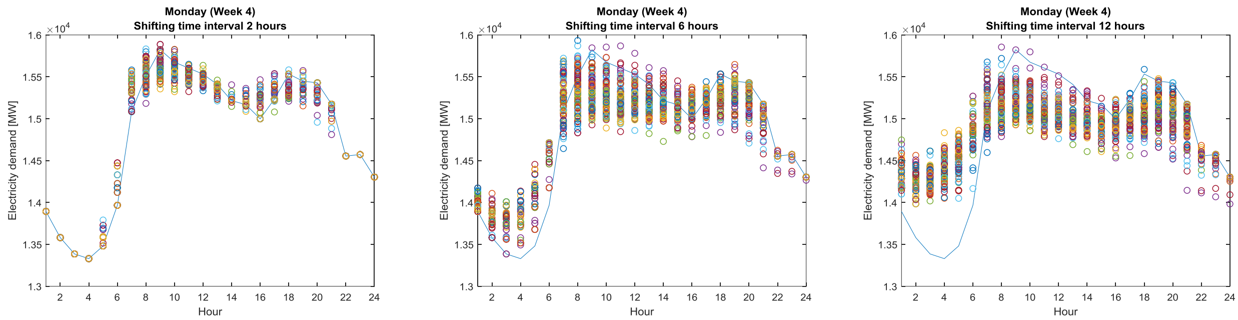

Fig. 5. The effect of shifting time interval on the demand response occurrences during a representative working day in Finland in 2030 in EC2016 scenario. Solid line describes the electricity demand profile in the case without demand response. Simulated demand reduction/recovery occurrences in the cases with demand response are presented with dot markers.

4 Conclusions

The research presented in this paper aims to assess the technical effectiveness of demand response as a demand-side flexibility option to mitigate variability in the energy system in Finland in 2030. The availability and long-term development of demand-side resource capacity is estimated in the residential and services sectors. The utilisation of end-user demand-side resource capacity is simulated based on the hourly residual demand variation during the day. The major findings are as follows:

- The results show that heating loads can provide a significant long-term technical potential for demand-side resource capacity in Finland in 2030. This demand-side resource capacity is not always available, as it varies according to the season and the time of the day. The temporal availability of demand-side resource capacities varies between 80–5600 MW. The availability is higher during the months from September to April because the electricity demand of demand-side resource applications is for the most part strongly dependent on the outside temperature and/or time of the day. This leads to higher utilisation of available demand-side resource capacity during the months from September to April when the residual demand is generally higher in Finland. It should be noted that end-use consumers' willingness to shift demand is not considered in this technical potential. Thus, it is assumed that available demand-side resource capacity is fully elastic within the defined shifting time interval. This can affect the maximum availability of demand-side resource capacity.
- Space heating and hot water storage are characterised with longer maximum duration for the shifting time interval, up to 12 hours, due to the physical storage capacities and/or the thermal

capacity of building structures. This enables preheating in earlier time of the day where demand is reduced during the peak hours and recovered during the off-peak 1 hours . In reality, the shifting time interval could be more constrained when the end-users individual preferences (e.g. loss of comfort) are taken into consideration. The results show that the annual utilisation of demand-side resource capacity decreases significantly when the shifting time interval becomes more constrained. For instance, the annual utilisation is reduced by 31% when the shifting time interval is limited to 6 hours. This illustrates that when the demand-side flexibility option is shiftable demand, the shifting time interval of demand-side resource application can be more significant factor for the demand flexibility than the maximum available demand-side resource capacity. The effectiveness to mitigate variability in the system can vary significantly between the demand-side resource applications because of their different characteristics. Moreover, small economic benefits and high costs of the required technologies and systems have been identified as major barriers for the utilisation of demand response in Finland [67]. Thus, for an effective exploitation of the variation in residual demand, it is important to focus on demand-side resource applications that have high electricity demand, and that are also flexible in terms of the maximum duration of shifting time interval.

- The utilisation of demand response can result in the formation of new demand peaks during the day when the residual demand variation during the day is high. This effect was found to be more significant in the scenario with higher share of wind power, and when the uncertainty regarding the day-ahead electricity demand was taken into account. Therefore, modelling the variability of wind power generation is recommended to estimate in a robust way the temporal effects of variable wind power generation. The results show that the variation in wind power generation during the day can have a significant effect on the magnitude of demand response occurrences. Furthermore, the differences between forecasted and measured electricity demand can lead to less optimal utilisation of demand-side resource capacity during the day.
- The utilisation of demand-side resource capacity results in balancing of residual demand in the day-ahead market. This smoothing effect reduces operating hours of thermal power production and the need for cross-border balancing by electricity imports during the peak hours. Furthermore, it leads to more efficient utilisation of wind power generation in the Finnish power market during the off-peak 1 hours. According to the sensitivity analysis, the ramping occurrences of district heating CHP units increase significantly with increased share of inflexible baseload nuclear power. The correlation between electricity and heating demand is reduced due to the utilisation of demand response. Therefore, the feasibility of demand response in district heating sector should also be considered in the energy systems with district heating CHP units in the future research.
- The changes in electricity exchange due to the utilisation of demand response show that in a power market that is highly interconnected, the effects are not necessarily restricted to the country (or bidding area) where demand response is utilised. For instance, the system efficiency gains can leak to the neighbouring countries as a consequence of excess production. The results show that excess production of district heating CHP increases when demand is reduced during the peak hours. This is due to the balancing of hourly district heating demand and supply. In some cases, the electricity price on the external market is high enough that the CHP heat conversion can still be more profitable than meeting the heat demand by using a heat-only boiler. Thus, the district heating CHP unit is kept online to meet the district heating demand and the excess electricity production is exported to the external market. This effect was found to be more significant in the scenario with higher share of inflexible baseload nuclear power. The overall effect on the system efficiency is dependent on the consequences that exported electricity has on the external market. Therefore, it is recommended that when the power markets are highly interconnected, the effects of demand response on the energy system operation are analysed within the whole market area, especially with regard to environmental effects.

Acknowledgements

The work presented here is financially supported through the Aalto University Energy Efficiency Programme, the STEEM (Sustainable Transitions of the European Energy Markets) project, the Doctoral School programme of Aalto University School of Engineering and REINO project mainly funded by Business Finland. The comments received during writing this paper are gratefully acknowledged.

Appendix A. Supplementary data

Table A. 1
Seasonal and diurnal change in production of different technologies and electricity exchange due to demand response in Finland in 2030 in EC2016/LIMITED EXCHANGE and EC2016/DEMAND PROGNOSIS scenarios. Averaged annual results of 100 simulations are divided between seasons and time of the day: Off-peak 1 hours (1:00 to 8:00), Peak hours (9:00 to 20:00) and Off-peak 2 hours (21:00 to 24:00).

		Change in production of different technologies and electricity exchange due to demand response [GWh]		
EC2016/LIMITED EXCHANGE				
Jan. to Apr.		Off-peak 1	Peak	Off-peak 2
	Thermal power	347	-267	-54
	District heating CHP	306	-233	-37
	Hydro power	13	1	0
	Critical import	61	-122	-15
	Critical export	-1	0	0
May to Aug.		Off-peak 1	Peak	Off-peak 2
	Thermal power	258	-321	-22
	District heating CHP	109	-147	-16
	Hydro power	118	-10	-4
	Critical import	0	-1	0
	Critical export	-38	0	0
Sept. to Dec.		Off-peak 1	Peak	Off-peak 2
	Thermal power	657	-438	-56
	District heating CHP	187	-164	-8
	Hydro power	-25	-68	-23
	Critical import	12	-66	-9
	Critical export	-1	0	0
EC2016/DEMAND PROGNOSIS				
Jan. to Apr.		Off-peak 1	Peak	Off-peak 2
	Thermal power	41	-67	-10
	District heating CHP	16	-14	-2
	Hydro power	130	-87	-35
	Import	372	-347	-62
	Export	-76	10	3
May to Aug.		Off-peak 1	Peak	Off-peak 2
	Thermal power	2	-139	0
	District heating CHP	46	-46	-4
	Hydro power	13	-166	-15
	Import	380	-138	-18
	Export	-78	-8	3
Sept. to Dec.		Off-peak 1	Peak	Off-peak 2
	Thermal power	9	-358	-26
	District heating CHP	19	-18	-1
	Hydro power	242	-62	-25
	Import	495	-267	-56
	Export	-61	12	1

Table A. 2
Seasonal and diurnal change in production of different technologies and electricity exchange due to demand response in Finland in 2030 in HIGH NUCLEAR and HIGH NUCLEAR/HIGH VRE scenarios. Averaged annual results of 100 simulations are divided between seasons and time of the day: Off-peak 1 hours (1:00 to 8:00), Peak hours (9:00 to 20:00) and Off-peak 2 hours (21:00 to 24:00).

		Change in production of different technologies and electricity exchange due to demand response [GWh]		
HIGH NUCLEAR				
Jan. to Apr.		Off-peak 1	Peak	Off-peak 2
	Thermal power	-7	-30	-3
	District heating CHP	362	-255	-39
	Hydro power	166	-121	-36
	Import	59	-75	-10
	Export	-149	142	20
May to Aug.		Off-peak 1	Peak	Off-peak 2
	Thermal power	-2	-28	0
	District heating CHP	65	-91	-13
	Hydro power	26	-165	-15
	Import	79	-101	-1
	Export	-353	96	13
Sept. to Dec.		Off-peak 1	Peak	Off-peak 2
	Thermal power	-3	-25	-1
	District heating CHP	190	-151	-12
	Hydro power	255	-87	-25
	Import	77	-158	-13
	Export	-314	320	42
HIGH NUCLEAR/HIGH VRE				
Jan. to Apr.		Off-peak 1	Peak	Off-peak 2
	Thermal power	-6	-23	-3
	District heating CHP	341	-236	-77
	Hydro power	145	-87	-44
	Import	37	-59	-11
	Export	-156	107	27
May to Aug.		Off-peak 1	Peak	Off-peak 2
	Thermal power	-1	-15	0
	District heating CHP	71	-100	-17
	Hydro power	36	-137	-25
	Import	51	-73	-6
	Export	-346	108	23
Sept. to Dec.		Off-peak 1	Peak	Off-peak 2
	Thermal power	-2	-23	-2
	District heating CHP	257	-199	-30
	Hydro power	215	-76	-30
	Import	65	-132	-17
	Export	-287	258	55

Table A. 3
Seasonal and diurnal change in production of different technologies and electricity exchange due to demand response in Finland in 2030 in HIGH NUCLEAR/HIGH VRE/LIMITED EXCHANGE scenario. Averaged annual results of 100 simulations are divided between seasons and time of the day: Off-peak 1 hours (1:00 to 8:00), Peak hours (9:00 to 20:00) and Off-peak 2 hours (21:00 to 24:00).

		Change in production of different technologies and electricity exchange due to demand response [GWh]		
Jan. to Apr.		Off-peak 1	Peak	Off-peak 2
	Thermal power	36	-23	-5
	District heating CHP	355	-417	-119
	Hydro power	156	-40	-25
	Import	-1	-26	-3
	Export	-129	6	11
May to Aug.		Off-peak 1	Peak	Off-peak 2
	Thermal power	-4	-84	-10
	District heating CHP	24	-170	-14
	Hydro power	129	-138	-26
	Import	0	0	0
	Export	-329	84	25
Sept. to Dec.		Off-peak 1	Peak	Off-peak 2
	Thermal power	41	-31	-9
	District heating CHP	386	-576	-98
	Hydro power	219	-66	-20
	Import	0	0	0
	Export	-176	16	7

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