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Energy Systems Scenario Modelling and Long Term Forecasting of Hourly Electricity Demand

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ABSTRACT

The Danish energy system is undergoing a transition from a system based on storable fossil fuels to a system based on fluctuating renewable energy sources. At the same time, more and more of the energy system is becoming electrified; transportation, heating and fuel usage in industry and elsewhere.

This article investigates the development of the Danish energy system in a medium year 2030 situation as well as in a long-term year 2050 situation. The analyses are based on scenario development by the Danish Climate Commission. In the short term, it is investigated what the effects will be of having flexible or inflexible electric vehicles and individual heat pumps, and in the long term it is investigated what the effects of changes in the load profiles due to changing weights of demand sectors are. The analyses are based on energy systems simulations using EnergyPLAN and demand forecasting using the Helena model.

The results show that even with a limited short term electric car fleet, these will have a significant effect on the energy system; the energy system's ability to integrate wind power and the demand for condensing power generation capacity in the system. Charging patterns and flexibility have significant effects on this. Likewise, individual heat pumps may affect the system operation if they are equipped with heat storages.

The analyses also show that the long term changes in electricity demand curve profiles have little impact on the energy system performance. The flexibility given by heat pumps and electric vehicles in the long term future overshadows any effects of changes in hourly demand curve profiles.

Keywords:

Scenarios analyses;
Energy system simulation;
Demand curve projections;
Heat pumps;
Electric vehicles;

URL:

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1. Introduction

Danish energy policy is committed to the short term objective of having more than 35% of the final energy consumption covered by renewable energy sources (RES) by the year 2020, with the more detailed stipulations that 10% of the transportation demand should be covered by RES and approximately 50% of the electricity demand should be covered by wind power [1]. By 2030, oil for heating should be phased out as well as the entire coal demand. By 2035, electricity and heating should rely completely on RES [2]. In the long term, the objective is to have a 100% RES penetration in the energy and transport sectors by 2050 [1], with the aim of combatting climate change [3, 4]. Denmark is a country of limited supply of storable RES [5] so high RES penetration is inevitably connected to large-scale exploitation of wind power and wind power has thus also hitherto played a pivotal role in the development of the Danish energy system [4] with a 2013 share of 33.6% of domestic electricity supply [6].

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This introduces a complexity into the future Danish energy system which has made Denmark an interesting case for analyses of high-RES energy systems as well as the centre point of a number of analyses focusing on high wind power scenarios [7-9], the role of electric vehicles in integrating wind power[10], the general role of the transport sector in future energy systems [11], limited biomass availability [5], large-scale use of cogeneration of heat and power (CHP) for district heating (DH) supply [12-14], smart energy systems [15], the role of storage in integrating wind power [16] and means of integrating wind power into national energy systems [17, 18].

The ENSYMORA project (Energy systems modelling, research and analysis) has targeted the future challenges of the Danish energy system through an integrated focus on methods and models for energy systems analysis including both methods and tools for supply scenario analysis as well as methods and tools for electricity demand projections. Research has investigated and compared high-RES scenarios [5, 19], short term projections of fluctuating RES including wind power [20] and wave power [21], long term forecasting of electricity demand using a combination of econometrics and high resolution existing demand pattern [22, 23] as well as policy implications of the transition to high RES energy supply [24, 25].

Many national scenario analyses including [5, 19] however have been based on existing demand curve profiles combined with demand curve profiles from new electricity demands including electric heating through heat pumps and electric vehicles. Electricity demand curve profiles will change though as a consequence of shifts between the relative weight of different demand sectors as well as due to the introduction of new technologies and behavioural changes over the coming decades. Therefore energy scenario analyses cannot focus on designing and simulating energy systems capable of meeting the demand variations of today but must focus on designing and simulating energy systems that are sufficiently robust to meet the demand variations of the future. For this reason, this article simulates a high-RES energy scenario for Denmark under different long term demand curve profile projections.

Secondly, with the required shifts in technology in vehicles and heating, the energy system is progressively becoming more and more based on electricity through electric heat pumps and electric vehicles. This introduces new and potentially controllable loads.

In this article we thus analyse A; the energy system impacts of projected changes in hourly electricity demand variations in a long term scenario based on a 2050 100% RES scenario for Denmark. At this point in time, we assume that electric vehicles and individual heat pumps are flexible; i.e., may be dispatched according to momentary energy system needs , and B; the energy system impacts in intermediate 2030 of having flexible or inflexible Electrical vehicles and individual heat pumps.

Research has already addressed future demand variations — e.g. based on price sensitivity of demands [26, 27] — however in this article we focus on system effects of changes in demand curve profiles. Demand curve profiles change due to changes in the composition of demand and especially due to the introduction of electrical vehicles and individual heat pumps. If demand by electrical vehicles and individual heat pumps is flexible this may partly balance variations in supply from fluctuating RES like wind power. However, today incentives for being flexible customers are lacking and if electrical vehicles and individual heat pumps are not flexible the integration of these new technologies may considerably increase the demand for peak capacity.

Section 2 introduces the tools and methods applied in the article; the hourly energy systems simulation model EnergyPLAN as well as a model for hourly demand curve forecasts. Section 3 details the construction of forecasted demand curves. Section 4 introduces a high RES scenario developed by the Danish Climate Commission and based on the scenario and demand curve forecasts introduced in Section 3, the system responses to different demand forecasts are analyses in Sections 5 and 6. Finally Section 7 concludes on the analyses.

2. Methodology

This section describes the main methodologies applied in this article; energy systems analyses using the EnergyPLAN model and electricity demand forecasting using the Helena model.

2.1. Energy systems analyses using the EnergyPLAN model

A simulation model with a high temporal resolution is required for conducting simulations of an energy system like the Danish with fluctuating energy sources playing a pivotal role in both the current and in the future energy system. Secondly, the Danish energy system is characterised by a very high degree of CHP production for DH and electricity generation. Thirdly, these CHP-DH systems are equipped with thermal storage allowing them to shift production of heat from times of increased electricity needs to times of reduced electricity needs. Furthermore, the system is experiencing a slow but gradual transitions towards electric vehicles or vehicles based on synthetic fuels which in turn affects electricity demands and electricity demand patterns, heat production and biomass usage patterns. Finally the energy system is becoming increasingly complex through exploitation of other synergies in the energy system – waste heat streams from industrial producers, use of heat pumps or resistance heaters in individual or DH applications. One simulation model that is capable of adequately handling these issues is the EnergyPLAN model (see comparison to other models in [28]). The EnergyPLAN has the following model characteristics:

- Focus on the integration of RES in energy systems. The model gives particular attention to the various fluctuating energy sources that may be utilised to cover electric and heat demands including wind power, off-shore wind power, photo voltaics (PV), geothermal power plants, hydro plants with and without dams, solar collectors for heat production either individual or DH connected.
- Entire energy system. The model includes the entire energy system with electric, heat, cooling, transport and industrial demands as well as the technologies to supply the different energy streams
- CHP, DH, heat pumps, storages. The model includes CHP plants of two types; back-pressure plants for small DH system as well as extraction plants for large-scale DH systems.
- Aggregated. All demands and productions are represented as one single unit with the average or total characteristics of the stock units of the various types.
- DH is modelled in three groups to represent small-scale boiler-based systems (Group 1), local CHP plants (Group 2) and large-scale systems based on extraction plants (Group 3)
- Deterministic – as opposed to probabilistic.
- One hour resolution / one year simulation horizon
- Endogenous priorities. The system gives highest priorities to production of a use-it-or-lose-it nature (wind, solar, wave) and minimum priority to the least efficient dispatchable units (boilers for heat generation and condensing mode power plants for power generation)
- Technical or economic optimisation. A range of technical operation strategies determine whether the model make CHP plants follow heat demands, follow a fixed profile or produce in a way to match both heat and electricity needs in the best possible ways. With economic optimisation, EnergyPLAN dispatches dispatchable units in the optimal way on a user-defined electricity market.

The model operates with a number of electricity demands. First and foremost what might be denoted the conventional electricity demand described with an annual aggregate and distribution indexes for each hour of the year. Secondly inflexible electric heating and cooling demands that are also stated as an annual aggregate combined with hourly distribution indexes. Thirdly electric vehicles which may be described in the manner of the two first categories – but which may also have flexible charging or even Vehicle-to-Grid (V2G) capability. Lastly a number of energy system internal electricity demands – including heat pumps for DH, electrolysers for hydrogen generation, charging of electricity storages.

In the analyses in this article, various means of flexibility are investigated, however it should be stressed that these analyses are performed using the one-hour resolution of EnergyPLAN. The flexibility of e.g. heat pumps and electric vehicles is clearly limited by the frequency at which these can be turned on and off without efficiency losses or excessive wear and tear, however any such constraints are under the one hour level.

Outputs include yearly, monthly and hourly productions and demands of all energy carriers from all modelled units as well as RES shares, carbon dioxide emissions and aggregated and annual investment costs, operation and maintenance costs, fuel costs and emission costs in case costs are included.

It should be noted, that EnergyPLAN is a single-node ("copperplate") model, thus any actual physical grid limitations within the system will not affect the operation as simulated in EnergyPLAN. This is a simplification, however as demonstrated in previous work [12,14,29,30], optimal operation of local CHPs and local integration lower demands of the transmission grid as well as transmission grid losses. The grid (transmission as well as distribution) will be affected by a move towards an energy system which relies more on electricity, however since this move is already undergoing and should occur, the grid will need to adapt. This however, goes beyond the current analyses.

Another potential shortcoming of the model and the school of models is represent is the fact that it does not endogenously handle probability or input variability; such variations must be handled exogenously if required. In particular, when performing long-term scenario analyses as in this case, with on the one hand expected climate changes and on the other hand naturally occurring shifts in demand, these have to be captured to be adequately reflected in the modelling. Climatic variations affecting productions (wind power, PV-production, wave power production, CHP production) and demands (heating and cooling needs) would optimally be included, These expected changes caused by climate change are small compared to variations from year to year though. From 2010 to 2014, the average yearly Danish wind energy varied from 89.6 % and 106.0% of the long-term average (see [31]). Thus inter-annual variations are considerable and cause significant fluctuations in productions. Since these analyses are tied to a certain scenario, this is not reflected here, as outputs are adjusted to reflect externally given scenario outputs (using the correction factor in EnergyPLAN, see [32] for details). In addition, previous analyses have revealed that the exact shape of the wind distribution profile is not pertinent for the evaluation of scenarios. Scenarios that integrate wind power well with the distribution profile of one year will also perform well with a distribution curve from another year.

Demand changes inflicted by climate change, are not reflected in the modelling. As for the demand curve variations occurring through shifts in behaviour and through shifts between sectors, these are reflected though the Helena forecasting (see Section 2.2).

EnergyPLAN has been used in a series of articles on supra-national energy scenarios (e.g. Europe [33]), national energy systems scenarios (e.g. China [34], Ireland [35] Croatia [36] and Romania [37]), regional or local energy scenarios[38,39] as well as in works detailing the performance of specific technologies in energy systems [40,41]. The model has been applied in nearly 100 peer-reviewed journal papers [42].

2.2 Hourly demand curve projections using the Helena forecasting model

From hourly metering of demand by individual customers we know that categories of customers have quite distinct demand profiles and contribute quite differently to the aggregate load. For one week in 2012 Figure 1 shows the aggregate load profile and the contribution by categories of customers, and Figure 2 shows the seasonal variation in the demand profiles by categories of customers.

From Figures 1 and 2, key observations are:

- The total demand has two daily peaks, a day-time and an evening peak.
- Demand is high on workdays and lower in weekend.
- Production sectors mainly consume during the day-time on workdays and households mainly consume at evenings and in weekends.
- The day-time peak is shortest for Public services, Industry has a longer day-time peak, and Private services have the longest day-time peak.
- Public services also have a small evening peak all days. This is due to public lighting.
- Friday has a shorter aggregate day-time peak than other workdays. Mainly Industry and Public services have a shorter day-time peak on Fridays.
- Over the year the level of demand is high during winter and low during the summer.
- The evening peak disappears during the summer.

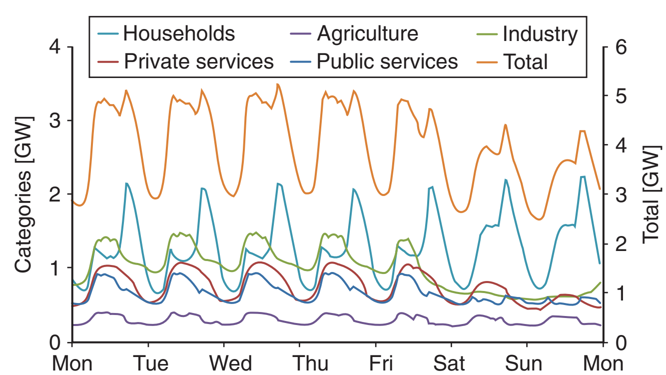

Figure 1: Hourly electricity demand by categories of customers. January 16 to 22, 2012 (data source: Panel data [54]).

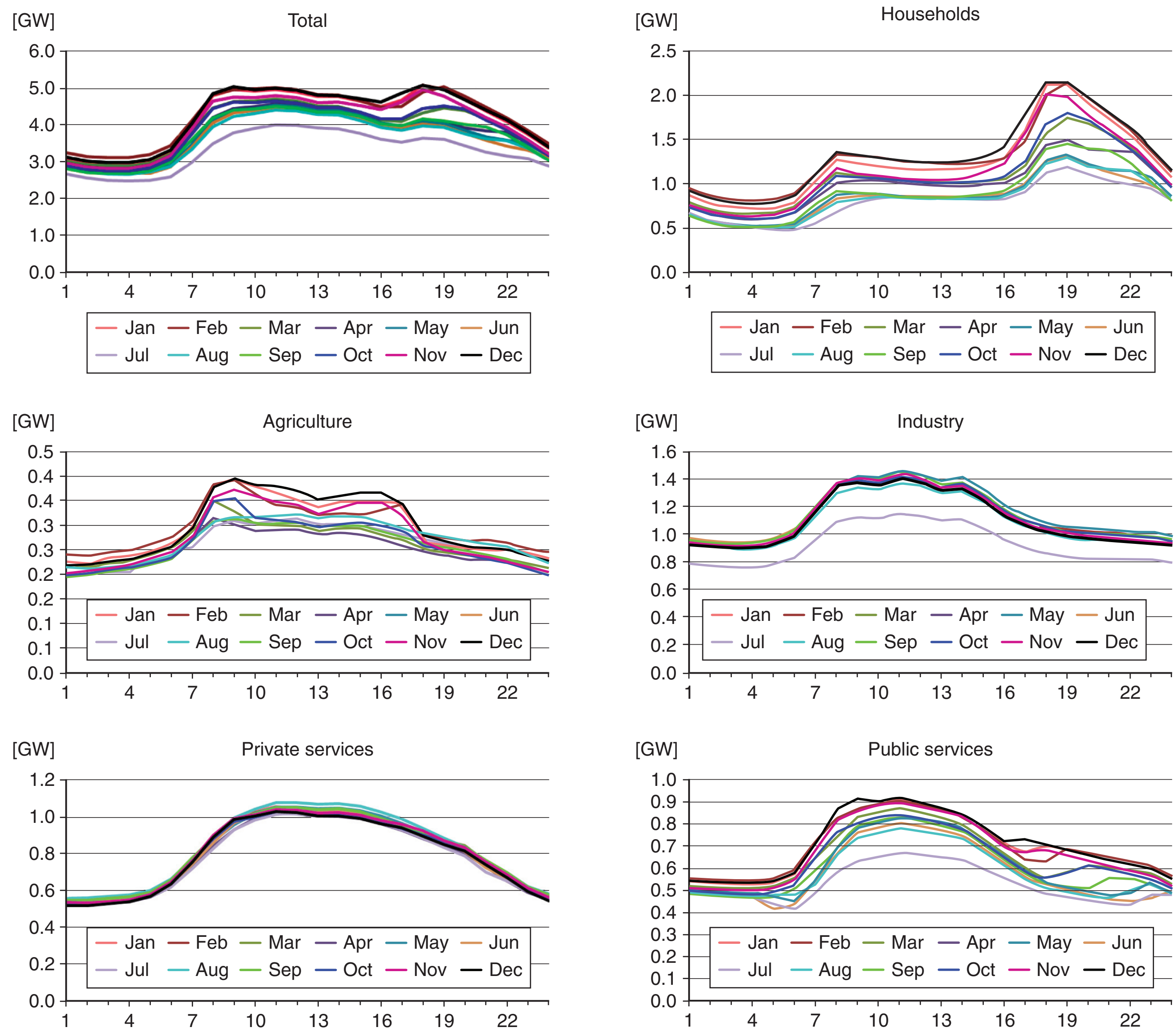

Figure 2: Average hourly electricity demand on workdays in 2012 for different categories of customers in Denmark. (Data source: Panel data [54].)

- Seasonal variation in the aggregate load is mainly due to variation within Households and Public services. (Demand by Industry and Public services is low in July. This is mainly due to companies having closed for summer holidays 1 to 3 weeks in July).

Modelling hourly electricity demand for each of the categories of customers shown in Figure 2 on data for 2010 we estimate the equation:

$$c^t = \sum_d a_d \;\; D_d^t \sum_m a_{d,m} \;\; D_m^t \sum_{\boldsymbol{h}} a_{d,m,\boldsymbol{h}} \;\; D_{\boldsymbol{h}}^t + \varepsilon_t \qquad (1)$$

where c^t is the electricity demand at hour t for a given category of customers and D_d^t, D_m^t, $D_{\boldsymbol{h}}^t$, are a number of zero/one variables representing various types of days (d)[†], 12 months (m) and 24 hours (h), respectively, and α_d, $\alpha_{d,m}$, $\alpha_{d,m,h}$, are coefficients. The $\alpha_{d,m,h}$, coefficients describe the shape of the daily demand profile for a given month (the shape of one curve in Figure 2), the $a_{d,m}$, coefficients describe the monthly level of demand (the relative position/level of one curve in Figure 2), and a_d describes the average hourly demand (average over the year) for the type of day (the absolute level of one curve). That is, for a given hour, demand is determined as: $a_d \bullet a_{d,m} \bullet a_{d,m,h}$. Finally, coefficients are normalized by imposing the restrictions:

for all *d*

$$\sum_{m=1}^{12} a_{d,m} = 12$$

and for all *d and m*

$$\sum_{h=1}^{24} a_{d,m,h} = 24$$

that is, the arithmetic mean of the coefficients is 1.0 and for a given h and m, if the $a_{d,m,h}$ is 1.2, for this hour demand is 20% larger than the average demand of the month, and if the $a_{d,m}$ for this month is 1.5, demand in this hour and this month is 80% (1.2 • 1.5 = 1.8) larger than the annual average for the type of day *d*. For details on the estimations and the estimated coefficients see [22].

3. Forecasting hourly Danish electricity demand

Using the model for projections we assume that the profile (that is the estimated coefficients) per category of customers is constant. As the weight of customers change, and as the categories of customers contribute differently to the aggregate load, the profile for the aggregate load will change.

Mathematically the aggregate load (hourly demand, hour *t*) in a future year *T* is calculated as:

$$C^{t,T} = \sum_i k_i^T \cdot c_i^t \tag{2}$$

where $k_i^T = E_i^T / E_i^B$ and E_i^B and E_i^T are the annual demand by category *i* in the base year B and the forecast years T, respectively, and c_i^t is the hourly demand by category *i* modelled by Eq.(1). k_i^T expresses the relative change in demand by category *i* from the base year till the year of projection. Projections of the annual electricity demand by categories of customers (E_i^T in Eq.(2)) are provided by the EMMA model [43]. EMMA forecasts annual energy demand by types of energy and links demand by categories of customers to economic indicators like prices, income and production in sectors. It is an annual econometric model that describes general effects of population, GDP, production, income, prices, and substitution between goods and types of energy. The model distinguishes 22 production sectors, three types of households and seven types of energy, and has for many years been used for official forecasts of energy and electricity demand by the Danish Energy Agency and the Danish TSO Energinet.dk, respectively. The latest version of the model is documented in [43]. A typical equation in EMMA links the annual climate corrected demand of a specific type of energy to an activity variable (e.g. the production in a sector or the number of households and income per household), energy prices capturing the substitution between types of energy, and includes a trend variable to describe changes in energy efficiencies. Equations are specified as log-linear with an error-correction-mechanism to describe long term equilibrium and annual adjustments towards the equilibrium allowing short- and long term elasticities to differ.

The latest baseline forecast of the annual electricity demand by the Danish TSO, Energinet.dk is shown in Table 1. For conventional demand the baseline projection reflects a central projection of the economic development by the Danish Ministry of Finance, the oil price projected by the international Energy Agency in World Energy Outlook 2013 [44] and a continuation of past trends and behaviour. From 2012 to 2020 GDP is expected to increase by 2% p.a. and from 2021 to 2030 by 1.3% p.a. The oil price is expected to increase from about 100$/bbl in 2013 to 140 $/bbl in 2035. The baseline also includes a projection of the introduction of electrical vehicles and individual heat pumps. Clearly with a changing energy system and further focus on energy savings projection of conventional demand is uncertain and especially the introduction of new consuming technologies like electrical vehicles and individual heat pumps is uncertain. However, in this analysis the projections are mainly used to illustrate qualitative effects of likely changes in the aggregated demand profile. So, although the absolute level of demand is uncertain the baseline may serve to illustrate qualitative changes.

From Table 1 it is seen that demand by households and agriculture is expected to increase moderately, that demand by industry and private service is expected to increase considerably and that demand by public services is expected to decrease. In addition, it is expected that the introduction of electrical vehicles and

Table 1: Projected electricity demand for aggregated categories of customers in Denmark. Source: [45] and own calculations in [46].

	Projected electricity consumption [GWh]			Change [coefficient k_i^T] in Eq. (2)	
	2012	2020	2030	2012–2020	2012–2030
Households	9750	9774	10042	1.0025	1.0299'
Agriculture	1847	1818	1895	0.9841	1.0255
Industry	7309	7983	8419	1.0922	1.1520
Private service	9604	9937	10801	1.0346	1.1246
Public service	2412	2272	2355	0.9418	0.9763
	30922	31783	33512	1.0278	1.0837
Electrical vehicles	0	140	660		
Individual heat pumps	73	431	778		
Total	30995	32355	34949	1.0439	1.1276

individual heat pumps in 2030 will add approximately 4% to the electricity demand.

It should be noted that the data in Table 1 are not comparable to the scenario by the Climate Commission from Section 4 which is targeting a society fuelled 100% by RES — and where transportation and individual heating to a large extent is shifted to electricity.

Looking at Figure 2, industry and private services mainly contribute to the demand during day-time on workdays. Assuming unchanged profiles per customer category the projected development in the annual demand implies that mainly the day-time peak increases. Looking at conventional demand Figure 3 shows the projected profiles for January and July for the years 2012, 2020 and 2030. Although the day-time demand increases more than the evening peak, in January the projected daily peak is still the evening peak and in general the aggregated demand profile changes only marginally.

Including the new demands by electrical vehicles and individual heat pumps, and assuming that these demands are not flexible, individual heat pumps are expected to have a demand profile identical to a normal heating profile in Denmark, and in the simple (but also most extreme) case electrical vehicles will be plugged in after work from 6 p.m. and be fully charged after 4 hours. However, as Danish taxes on electricity consumed by households are considerably higher than taxes paid by companies, charging at work will be a perfect employer benefit. Therefore, as an alternative we analyse a profile where $^1/_2$ of the electrical vehicles are charged at work from 8 a.m. and the other $^1/_2$ is charged at home from 6 p.m. That is, compared to the most extreme case demand by electrical vehicles is split between two periods reducing the peak demand by electrical vehicle to the half. For 2030 the effects on the hourly demand in January and July are shown in the Figures 4 and 5.

As seen from Figure 4, while changes in the conventional demand changes the level of the demand profile, the introduction of new demand categories changes both the level and the hourly demand profile.

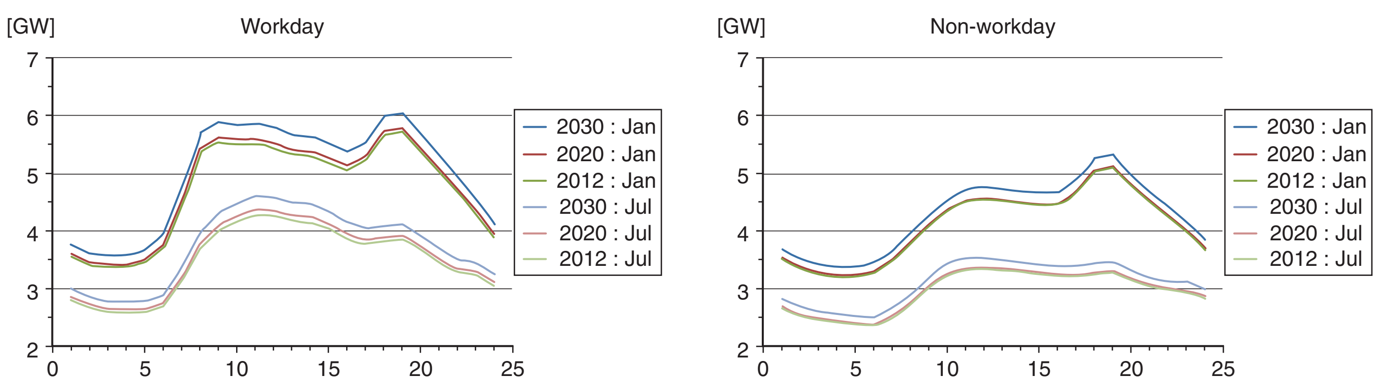

Figure 3: The hourly demand profile for existing categories of customers, 2012, 2020 and 2030, January and July

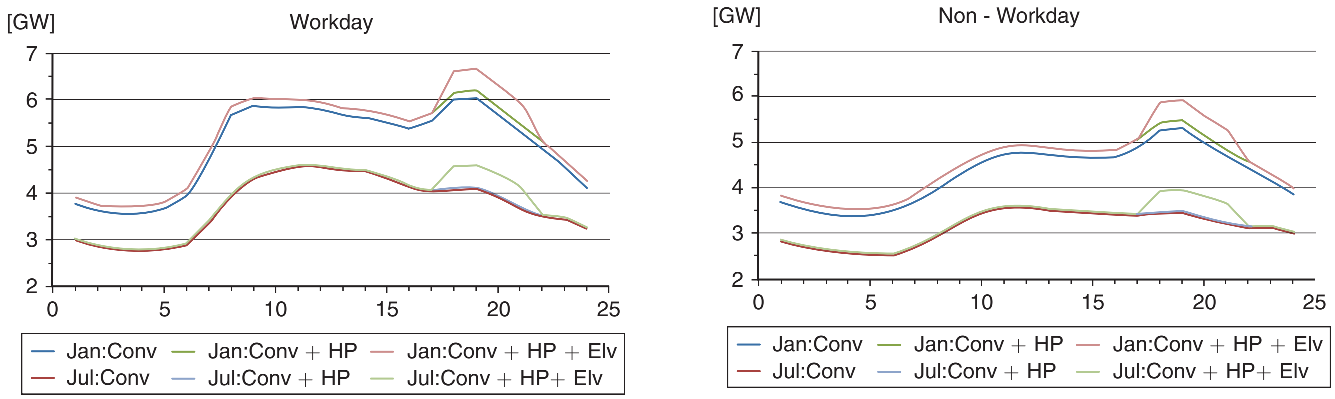

Figure 4: Effects on the hourly demand from the introduction of individual heat pumps (HPs) and electrical vehicles (EVs) charged after work in 2030.

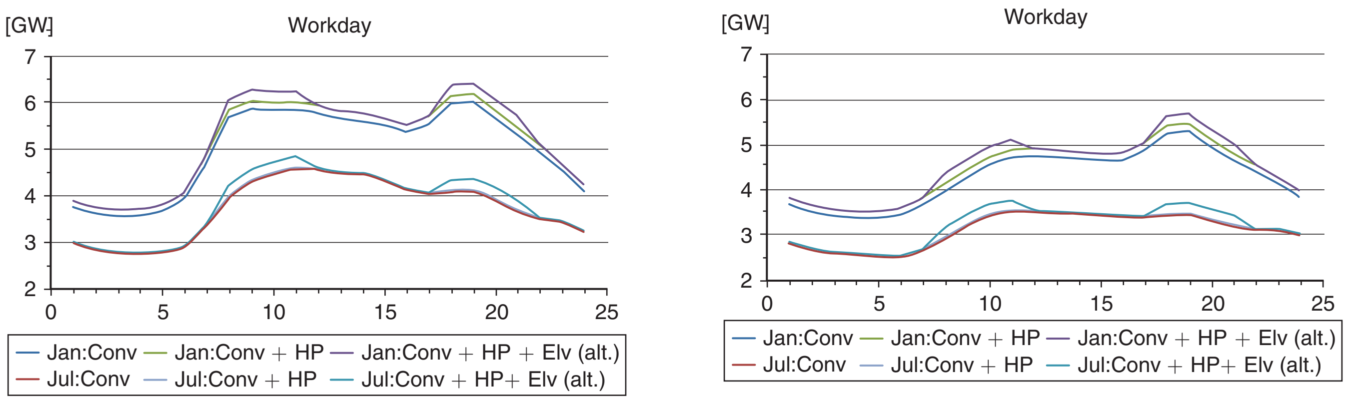

Figure 5: Effects on the hourly demand from allowing half of the electrical vehicles to be charged at work (EV(alt)) in 2030.

Individual heat pumps mainly change the seasonal demand profile; demand increases considerable during the winter (represented by the profile for January, where demand is already very high) while the demand during summer is almost unchanged. Electrical vehicles mainly change the daily profile while seasonal variations are limited. In the worst case where all electrical vehicles are charged after work the evening peak increases app. 10% (shown in Figure 4), while this is reduced to an increase of app. 5% if half of the vehicles are charged at work (shown in Figure 5). That is, seen from the perspective of the electricity system charging part of the vehicles at work is preferable, but this reduces the tax revenue considerably.

Combining Figures 3, 4 and 5, Table 2 shows the demand in January at 7 p.m. assuming different charging profiles for individual heat pumps and electrical vehicles. If heat pumps and electrical vehicles are flexible customers and therefore not using electricity

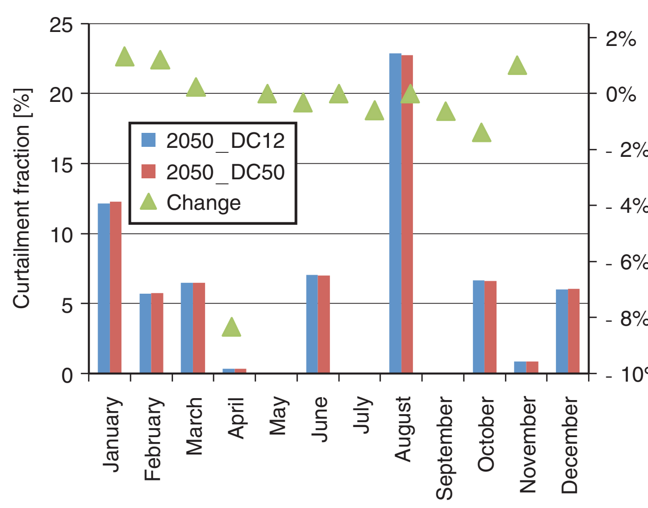

Figure 6: Curtailment fraction for off-shore wind in CC2050 with electricity demand curves from 2012 (2050_DC12) and 2050 (2050_DC50). Note, the change between the curves shown along the right axis is not in percentage point but in percent.

Table 2: Aggregated demand January at 7 p.m. in GW assuming different demand profiles by individual heat pumps and electrical vehicles.

	2012	2030			
	total [GW]	Conventional [GW]	Conventional and individual heat pumps [GW]	Conventional, individual heat pumps and electrical vehicles charged after work [GW]	Conventional, individual heat pumps and electrical vehicles charged at work anf after work [GW]
Januar at 7 p.m.	5.72	6.03	6.20	6.65	6.42
%-change from 2012		5.4	8.4	16.3	12.3

at peak hours, due to increased conventional demand the peak in January at 7 p.m. is expected to increase about 5%, only. If individual heat pumps follow a standard heating profile in Denmark, heat pumps are expected to increase the peak demand by additional 3%. In the worst case where all electrical vehicles are charged after work from 2012 till 2030 the average peak at 7 p.m. in January increases from 5.72 GW to 6.65 GW or about 16%. In July the daily peak at 7 p.a. increases from 3.85 GW to 4.60 GW or about 19%. That is, the %-change is larger in the summer than in winter, but the absolute change is 25% larger in the winter than in the summer. As is seen from Table 1 the aggregate demand is expected to increase 12.8% from 2012 to 2030. That is, in the worst case the peak demand increases somewhat more. If only $^1/_2$ of the electrical vehicles are charges after work the increase at 7 p.m. is reduced to about 12%. That is, depending on the flexibility of individual heat pumps and electrical vehicles the expected demand at 7 p.m. in January 2030 is between 5% and 16% larger than in 2012.

For the subsequent analyses of 2050, we only apply the shape of the demand profile; not the actual size as we combine the shapes with the electricity demand of the mentioned scenario by the Climate Commission. One element which has not been included in the assessment of the demand profile is energy savings with an impact on the temporal distribution of the electricity demand; where some electricity demands like refrigeration, freezing and stand-by demands are relatively stable throughout the 24h of the day, other demands are more related to behavioural pattern — cooking, entertainment, domestic hot water (DHW) (if produced by electricity), ventilation and washing/drying - or external factors such as the presence of daylight and thus notably indoor and outdoor illumination. Savings in different areas will thus impact the demand profile differently.

For the analyses of 2030, hourly variations curves for the classic electricity demand, the individual heat pumps and electric vehicles will be used.

4. High-RES scenario for Denmark

Denmark has a long-term objective of being independent of fossil fuels in the energy and transport sectors by 2050[1]. With that aim, the Danish Government established a so-called Climate Commission in 2008 given the task of making suggestions as to how this vision might be reached [47]. This work resulted in a series of suggestions including increasing deployment of RES, transportation based on electricity and biofuels, focus on energy efficiency and a smart and flexible electricity system. The work also included holistic scenario design and energy systems simulations though only for limited simulation periods.

4.1. The Danish Climate Commissions' year 2050 100% Scenario

Two different scenarios were established by the Climate Commission for 2050 (CC2050); the Ambitious and the Unambitious — labelled Future A and Future U respectively. In this article, we use Future A as our reference system. This scenario has been adapted to the EnergyPLAN model in previous work [48] where it is described in detail, thus in this article, only the main parameters are included. One important aspect of the CC2050 scenarios; the scenarios do not detail the electricity demand by sectors nor by temporal distribution.

In the CC2050 Future A scenario, the electricity demand is 88.5 TWh (See Table 3) compared to 35.7 TWh in 2010 for all demands [49]. The significant

Table 3: Danish electricity demand in 2050 according to the Ambitious Scenario of the Danish Climate Commission. AHPs are absorption HPs typically utilising low-temperature (60-80°C) geothermal reservoirs. Based on [50].

Demand sector	Annual demand [TWh]	Aggregated sectors	Annual demand [TWh]
Electric vehicles and trains	20.5	Electric vehicles & weighted grid loss	21.2
Geothermal energy	0.5	District heating HP and Absorption HP (AHP) & weighted grid loss	5.6
District heating HP	4.7		
Commercial HP	0.6	Individual HP & weighted grid loss	4.1
Residential HP	3.3		
Industrial processes	17.1	Demands following a fixed curve. Including trains & weighted grid loss	48.4
Industry - other	6.3		
Commercial - other	11.8		
Residential - other	9.9		
Biofuel production	8.7	Biofuels (assumed hydrogen-based) & weighted grid loss	9.2
Grid losses	5.1		—
Total	88.5		88.5

increase is due to the electrification of new sectors. In Table 3, the first two columns show the demand sectors as listed in the original scenario where the separate grid losses are a noticeable component. EnergyPLAN treats all electricity (and DH) demands as supplied ex works thus electricity demands must include grid losses. Thus, the separately given grid losses are distributed proportionally on specific demands. In addition, certain categories are aggregated to reflect the aggregation level in EnergyPLAN. Final demands modelled in EnergyPLAN are thus shown in the two last columns.

DH demands amount to 36.9 TWh including DH grid losses. Individual heat demands (i.e. non-DH covered space heating and Domestic Hot Water (DHW) production) amount to 16.74 TWh covered by 1.95 TWh of biomass boilers (η = 0.7) and 4.10 TWh of electricity for HPs (COP = 3.75).

The production system is characterised by a large share of wind power both off-shore and on land. Wave power and photo voltaics also play major roles — see Table 4 for details. The scenario has a large increase in the interconnection capacity to neighbouring Sweden, Norway and Germany, however since our goal is to analyse the impacts on the energy system performance and flexibility, the system is modelled in island-mode. One reasons is that including the planned 12 GW of

Table 4: Scenario parameters for CC2050. Information based on [47,48,50,51].

Unit	Installed capacity [MW_e]	Characteristics
Off-shore wind	14600	Production 59.7 TWh ~ 4090 full-load hours
On-shore wind	4000	Production 14.3 TWh ~ 3568 full-load hours
Wave power	450	Production 1.00 TWh/y ~ 2222 full-load hours
Photovoltaic	3250	Production 3.00 TWh/y ~ 923 full-load hours
Condensing mode capacity	15000	η_e=45%; Sized to be able to function as backup
CHP capacity	2500	η_e=40%; η_h=50%. Annual DH demand 36.9 TWh (also covered by DH HP and waste incineration CHP)
Waste incineration	365	Fixed fuel input 12 TWh/y. η_e=26.7%; η_h=77.3%
DH HP	4500	COP 3.75
Individual HP	837	COP 3.75. Annual individual heat demand of 16.9 TWh covered by solar 0.8 TWh, biomass boilers 1.3 TWh and HP 14.7 TWh (the latter is based on the electricity demand in Table 3 - excl grid loss)
Electrolyser synthetic fuel	3100	η=68%. Capacity is twice the capacity required for base-load production of the annual hydrogen demand
Interconnection capacity	(12000)	To Norway, Sweden and Germany

interconnection capacity would not test the energy system's flexibility to any extent and a second reason is that while nominal interconnection capacity might be significant, useable interconnection capacity would be significantly less during the relevant windy periods assuming similar developments in neighbouring countries. In EnergyPLAN terms, the system is thus modelled in a technical regulation strategy 3 where the model seeks to balance both heat and electricity systems without the use of import/export.

The scenario lacks details on EV technology; charging, battery and potential discharging, hence the same ratio between aggregate annual demand and installed battery capacity/charging power as in the 2030 Scenario are used (see next section). It is assumed that EVs may discharge back to the grid (so-called V2G; Vehicle to Grid) with a cycle efficiency of 0.81 (=0.9^2). The sensitivity of using this ability is investigated further in the 2030 scenarios.

While this scenario is a specific case with a specific composition of the energy system, it is very much aligned with independent work by researchers in e.g. the CEESA project [52,53], the Danish Society of Engineers (IDA)[54-56] as well as with official Danish targets of having a 100% RES-based electricity and heat supply by 2035 — primarily based on wind power, and a 100% RES-based energy system by 2050. In all scenarios, wind power plays the dominant role, heating and transportation is switched to electricity where possible and biomass use is strongly restrained. Thus, while results naturally apply only to the specific case, they do apply more generally to the Danish energy future as well as to energy futures of countries with a similar composition as Denmark. It is however impossible to make generally valid statements based on a case considering that all areas have different energy circumstances and that transition to 100% RES-supply should be adapted to local conditions.

4.2. Intermediate 2030 scenario

In order to make the 2030 analyses, a corresponding scenario is set up for this year. Electricity demands are based on the forecast described in Section 3 — see Table 5. As stated in Section 1, by 2030 the ambition is to have phased out coal entirely and have phased out oil from heating. The projection in Section 3 reveals a heat demand for individual heat pumps of 1.6 TWh by 2030, however this projection is based on trends rather than the target of an oil-free heating supply in 2030. Thus, we apply the hourly variation from Section 3 but the aggregated total from the 2050 Scenario — i.e. 4.1 TWh cf Table 3.

The projection does not detail district heating heat pumps; the same level as the 2050 scenario is used.

The EVs demand for 2030 in Table 5 is modest compared to the level in 2050; the remainder is assumed fossil-based and does not impact the workings of the rest of the energy system. The EV demand corresponds to 300 000 vehicles each using 2.2 MWh annually + 5.7% grid losses. For comparison, the number of personal vehicles in Denmark January 1st 2015 was 2.33 million in addition to which comes 0.44 million vans/lorries/road tractors and 13408 busses[57]. For the analyses, a charging capacity of 10 kW and a battery capacity of 30 kWh is use, in line with[58]. Thus, there is a total charging capacity of 3 GW and a total battery capacity of 9 GWh for the 2030 Scenario. It should furthermore be noted, that it is assumed that the electricity demands are measured at the grid-side of the battery charger for both the 2030 and the 2050 Scenario.

It should be noted that the electricity demand for electric vehicles in the 2050 scenario is very large (20 TWh[50] or 21.2 TWh incl grid losses) compared to the 2030 scenario's 0.7 TWh. Contributing factors include, that in the 2050 scenario, EVs have a 90% penetration in terms of fuel demand for personal vehicles, and 70% for busses and lorries[50].

Table 5: Danish electricity demand in 2030 according to 2015 prognosis. Including the same relative grid loss as in 2050.

Demand categories	Annual demand [TWh]
Electric vehicles & weighted grid loss	0.70
District heating HP and Absorption HP (AHP) & weighted grid loss	–
Individual HP & weighted grid loss	0.91
Demands following a fixed curve. Including trains & weighted grid loss	38.51
Biofuels (assumed hydrogen-based) & weighted grid loss	0
Total	40.12

Photo voltaics and wave power are modelled at half the level of the 2050 Scenario — i.e. 1625 MW and 225 MW and as 2030 is close to year 2035 at which point all electricity should be RES-based. The installed capacity of on-shore wind power is kept at 4000 MW in line with the 2050 scenario. Off-shore wind power is 9000 MW, corresponding to an un-curtailed annual production of 36.81 TWh.

All other factors are identical to the 2050 scenario. Furthermore, for both the 2050 and the 2030 scenarios, electricity production variation on wind turbines are based on actual 2014 data for off-shore and on-shore wind turbines respectively from the Danish TSO[6], while photo voltaic, and wave-power demand variations are generic Danish variations from the EnergyPLAN library. Newer data was regrettably not available.

Using generic data for solar and wave power does introduce an element of error as wind and wave clearly is strongly correlated though with a production up till six hours out of phase. Wind and solar is also slightly correlated, but mainly in out-of-the-ordinary very high-wind situations. For this work, distributions of wave power were available for measurements from 1999 and 2001 (see [59] for methodology). To test the impact of the choice, scenarios were modelled with three different distributions; the 2001 (which is used in all other analyses in this article), the 1999 distribution and a constant distribution. Aggregated annual results were generally not affected by the choice of distribution. Approximately 1 ‰ less off-shore wind power was curtailed when using a constant production from wave-power than when using the 1999 or 2001 distribution. Observing individual hours, effects are naturally larger, however this article focuses on aggregated annual effects. A primary reason for this negligible effect of the distribution curve is the fact that wave power in the scenarios generate 0.5 TWh per year while wind power generate approximately 50 TWh per year, thus the share pales by comparison.

District heating demand variations are based a case from Aalborg with a 30% demand reduction in room heating demand (see [38]).

4.3. Scenario Overview

The 2030 and the 2050 scenarios are modelled as listed in Table 6.

For individual houses using HPs, the same heat demand curve is used across scenarios. In the 2030 Fix, there is no flexibility thus electricity demands follows heat demand exactly (and the electricity demand is in fact included into the classic demand) – but for the other scenarios, HPs are dispatchable from the

Table 6: Scenarios. DC12 and DC50 signify Demand Curve 2012 and 2050 respectively.

Scenario	Demand	Production	Hourly Variation profile
2050_DC12	As in CC 2050	As in CC 2050 100% RE	EV and HP dispatched by EnergyPLAN Normal demand according to fixed hourly demand curve for 2012
2050_DC50	As in CC 2050	As in CC 2050 100%% RE	EV and HP dispatched by EnergyPLAN Normal demand according to fixed hourly demand curve for 2050
2030 Flex	As in 2030 prognosis	100% RE in heat and electricity	EV and HP dispatched by EnergyPLAN Normal demand according to fixed hourly demand curve for 2030
2030 Fixed	As in 2030 prognosis	100% RE in heat and electricity	EV and HP according to fixed demand curves. HP with one temperature-derived curve EVs with three alternative demand curves: -Charging during night -Charging from 18-21 in the evening -Charging half from 8 - half from 18 Normal demand according to fixed hourly demand curve for 2030

EnergyPLAN model, which utilises a storage to minimise electricity exports. Unless otherwise noted, the storage corresponds to seven days of average heat demand.

Mathiesen et al state *"Smart Energy System focuses on merging the electricity, heating and transport sectors, in combination with various intra-hour, hourly, daily, seasonal and biannual storage options, to create the flexibility necessary to integrate large penetrations of fluctuating renewable energy"*[53]. This is in line with the Flex-scenario where EVs and HP are dispatched according to momentary system needs. The traditional electricity demand is not flexible in this scenario, however as Kwon & østergaard has determined, effects of this are very limited indeed[48].

5. System response to demand forecasts for 2050

The energy plan model gives priority to electricity production made from use-it-or-lose-it RES production and subsequently production in CHP mode whereas electricity made in condensing mode is avoided if possible. The level of condensing mode operation is thus

Table 7: District heating production for CC2050 with 2012 electricity distribution (2050_DC12) and forecasted 2050 electricity distribution (2050_DC50). Numbers 1–3 refer to the district heating groups in EnergyPLAN.

District heating [TWh]	2050_DC12	2050_DC50
Boiler 1	2.68	2.68
Heat Pumps 2	5.96	5.96
Boiler 2	0.05	0.05
CHP 2	2.17	2.16
Waste 2	3.32	3.32
Solar 2	0.90	0.90
Heat Pumps 3	11.93	11.94
CHP 3	0.00	0.00
Waste 3	5.95	5.95
Solar 3	1.62	1.62
Boiler 3	0.01	0.01
Industrial CHP 3	2.45	2.45
Sum	37.04	37.04

Table 8: Electricity generation for 2050 with 2012 electricity demand curve (2050_DC12) and forecasted 2050 electricity demand curve (2050_DC50).

Electricity [TWh]	2050_DC12	2050_DC50
Industrial CHP	3.70	3.70
Wind Off-shore	55.95	55.94
Wind on-shore	14.29	14.29
Wave	1.00	1.00
PV	3.00	3.00
CHP	1.74	1.73
Condensing mode power plants	13.19	13.20
Import	0.00	0.00
Export	0.00	0.00
Sum	92.87	92.86

an indication on how well a system integrates fluctuating renewable energy sources, as also discussed in [60,61]. Similarly, within heating, priority is given to use-it-or-lose-it technologies, followed by HP, CHP and boilers.

Effects on the system performance according to choice of demand curve (DC12 or DC50) are marginal according to the EnergyPLAN simulations. Heat production is practically unaffected on an aggregate annual basis and so is the electricity system (See Tables 7 and 8).

In the analysis, any excess that cannot be integrated through dispatching dispatchable units appropriately, is reduced through three chosen successive steps: a) CHP is replaced by boiler production; b) boiler production is replaced by electric boiler production and c) off-shore wind power production is curbed.

The first two steps render little assistance thus curbing or curtailing off-shore wind power production dominates. The curtailment fraction (see [42]) varies over the year with monthly averages ranging from nil to nearly 23% (See Figure 5).

One difference between the two scenarios is that the curtailment fraction tends to be higher with the 2050 demand profile during the winter months and vice versa higher during the summer months with the 2012 profile as a result of slight change in the annual distribution of the electricity demand.

6. System response to flexible or static operation of EVs and HPs in 2030

The second set of analyses take their starting point in a 2030 situation with less electric transportation and less electric heating. Meanwhile, the system is analysed under four different circumstances as listed in Table 6; with heat pumps and electric vehicles dispatched by EnergyPLAN and using three defined demand profiles; one fixed for heat pumps and two alternative EV charging patterns. Furthermore, the scenarios where EVs and HPs are dispatched by EnergyPLAN are also analysed for sensitivity to key input factors; EV battery size, EV charging capacity, V2G ability and storages for heat pumps in individual dwellings.

Using a fixed demand profile for HPs and EVs reduces the off-shore wind utilisation while more electricity will be produced on dispatchable thermal plants – CHP and condensing mode plants. The lowest utilisation of off-shore wind power – and thus the highest curbing – is in the case where EVs are charged in the evening from 18-21 corresponding to a charging pattern where people return from work and plug in the vehicle. Compared to this, off-shore wind power has a marginally higher utilisation with the other EV fixed charging profiles. For the flexible scenarios, utilisation is between 1.4% and 5.5% higher. The lowest effect is under the standard conditions as defined in Section 4 and with 50% higher charging capacity (thus 4500 MW) and with 50% additional battery capacity (thus 13.5 GWh). Adding seasonal heat storage enables a 2.9% higher utilisation of off-shore wind power but even a storage with a contents of one average week, increases the utilisation of off-shore wind power by 2.2%. Note of course, that such storage need not be a fully conventional storage with a fluid storage liquid; the building mass in itself has a large storage capacity. What really increases the

Table 9: Electricity production and corrected fuel consumption for scenarios 2030 Fixed and 2030 Flex. Import and export in all scenarios is zero.

	Fixed HP and EV		Flexible HP and EV						
[TWh]	EV 18 21	EV morn+ evening	Standard	V2G	Heat storage	V2G + Heat storage	EV 4500	Battery 13.5	Battery 13.5 V2G 4500
Industrial CHP	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
Wind Off-shore	18.8	18.82	19.07	19.55	19.35	19.8	19.07	19.07	19.83
Wind on-shore	14.26	14.26	14.26	14.26	14.27	14.27	14.26	14.26	14.26
Wave	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PV	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
CHP	1.44	1.44	1.41	1.41	1.41	1.41	1.41	1.41	1.41
Condensing mode power plants	5.06	5.04	4.82	4.44	4.66	4.31	4.82	4.82	4.22
Sum	45.26	45.26	45.26	45.36	45.39	45.49	45.26	45.26	45.42
Corrected Fuel consumption	56.44	56.41	55.86	55.04	55.52	54.75	54.75	55.85	54.54

integration of off-shore wind power is the utilisation of V2G, which also reduces condensing mode power generation significantly; up to 16.6% with additional charging/discharging capacity of 4500 MW and additional battery capacity of 13.5 GWh

Thus, even with the limited demands for EVs and HPs in this 2030 scenario, there is a significant flexibility to be harnessed and exploited for the purpose of optimising the integration of wind power which on the one hand decreases the curtailment of wind power and on the other hand decreases the use of condensing power generation

Another observation from Table 9 is, that whether all EVs are charged during the evening or half of the EVs are charged at work from 8 a.m. has little effect for the system. However, allowing half of the EVs to be charged at work considerably reduces the tax revenue from electricity taxes.

In the systems analyses, condensing mode power production capacity is merely included at the level required to satisfy any discrepancy between electricity demands and productions based on fluctuating RES and CHP. Thus, the installed capacity and thus associated costs vary between the scenarios. Charging EVs between 18 and 21 in the evening sets the highest requirement for condensing mode capacity at 5652 MW, followed by charging in the morning and evening at 5415 MW. The flexible HP and EV scenarios range from 5060 MW for the two scenarios with large heat storage to 5249 MW for the other flexible scenarios. Thus, capacity reductions between 237 and 592 MW (4.2 to 10.5%) may be realised by a; spreading the fixed charging pattern of EVs b; introducing flexible charging of EVs and c; introducing flexible dispatch of individual heat pumps combined with heat storages.

7. Conclusion

This article has investigated the evolution of the Danish electricity demand in the medium term (2030) and the long term (2050) based on energy systems simulations of an energy system with 100% RES in heating and electricity (2030) and with 100% RES in heating, transportation and electricity supply (2050).

In the medium term, it is found that the flexibility of individual HPs and EVs may assist in the integration of wind power even though the individual heat pumps only cover the part of the heat demand (3.4 TWh) that is not covered by district heating (36.9 TWh) and that only 300 000 private vehicles are converted to electricity. Curtailment of off-shore wind power is reduced, electricity production in condensing mode is decreased, installed capacity of same may be reduced as will primary energy supply.

In condensing mode power generation, capacity reductions between 237 and 592 MW may thus be realised depending on how EVs and HPs are introduced to the energy system. In the worst of the cases analysed, only 18.8 TWh out of an uncurtailed off-shore wind power production of 36.81 TWh is used, while in the best case with V2G and extra battery this number is 19.83. Thus, an extra TWh of electricity is integrated by this means. It should be noted though, that the installed off-shore wind power capacity is not adjusted to match the annual demand; it does actually produce too much. Thus, with a closed island system there will inevitably be off-shore wind power curtailment.

Changing the EV charging schedule from a fixed 18–21 in the evening to a morning plus evening charging decreases wind power curtailment and condensing mode power operation, but making them flexible to the extent of even enabling V2G operation maybe increase benefits considerably. Of course, charging vehicles at work will have derived effects in the form of reduced tax revenues — assuming vehicles are charged at work with low-tax electricity.

In the long term (2050), the entire personal vehicle fleet will be changed to electricity adding even more flexibility to the system. The changes in the traditional electricity demand coming as a consequence of shifts in the weights of consumption sectors will have very limited effects on the energy system performance – particularly since the energy system is characterised by such large flexible loads. Using off-shore wind power curtailment as metrics for assessing the system's ability to integrate wind power, results vary over the year. Generally, the monthly curtailment share is within a 2% band when changing from the 2012 load curve (LC_12) to the 2050 load curve (LC_50). One month has a change of more than 8%, however this change is between two small numbers. Observing annual production figures, slight differences in the order of 0.01 TWh exists between some production and demand categories with LC_12 compared to with LC_50. This relates to off-shore wind power, CHP, condensing mode power production and heat pump demand. With LC_12, off-shore wind power, CHP production and HP demand are all 0.01 TWh higher while condensing mode power generation is 0.01 TWh less with LC_2012. These numbers should be taken with caution though, as differences represent the last significant digit in EnergyPLAN simulation outputs.

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