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Electricity cost effects of expanding wind power and integrating energy sectors

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ABSTRACT

Recently, questions have arisen in Denmark as to how and why public funding should be allocated to wind power producers. This is, among other reasons, due to pressure from industrial electricity consumers who want their overall energy costs lowered. Utilising existing wind power subsidies across energy sectors may be an effective means of dealing with these concerns. The following article takes the case of a community owned renewable energy project as a microcosm for the entire Danish energy system. The local project seeks to integrate energy sectors so as to create physical and financial conditions which could allow wind power producers to reduce their reliance on subsidies. It is found that the strategy may be effective in lowering the overall energy costs of electricity consumers. Further, it is found possible to scale up this strategy and realise benefits on a national scale.

Keywords:

Integration of energy sectors;
Renewable energy subsidies;
Electrified transportation
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1. Introduction

In Denmark, and elsewhere, public subsidising of wind power producers is intended to help increase the country's share of renewable energy. Here, the term public subsidising is used in reference to both money allocated to energy producers by government agencies, and to the present Danish system in which wind power subsidies are financed by the electricity consumer. These subsidies enable wind farms to compete on the same markets as fossil fuel burning units and in this way deal with a major issue regarding the integration of renewables in the energy system. However, reducing the amount of fossil fuel usage in energy systems requires not only an increase in the amount of electricity supplied by renewable sources but a corresponding increase in the consumption of this renewable electricity as well. Increased consumption will be dependent on the potential to replace fossil fuel usage in the energy system. Therefore it will likely be necessary to convert fossil fuel based units in the transportation and heating sectors to run on electricity. By utilising subsidies across energy sectors (electricity, heating and transportation), both production and consumption side initiatives could be funded from the same initial public monies. This could consequently provide a more effective means for countries such as Denmark to integrate renewables into their energy systems.

Integrating energy sectors through increased consumption of electricity for heat and transportation is a concept which has recently been advocated under the smart energy systems approach [1, 2]. The approach has been suggested as a means of introducing fluctuating renewables into energy systems in an affordable and financially feasible way. The approach proposes that energy systems transition from their reliance on the supply side flexibility of stored energy in the form of fossil fuels to a demand side flexibility which would come from electric based transport and heating units.

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Analysis has shown that this transition is indeed possible and will provide substantial socio-economic benefits [3, 4]. Moreover, integrating energy sectors will be facilitated by the use of renewable energy sources, the creation of distributed energy networks, community involvement in the implementation of these new distributed systems, and an overall focus on sustainability in future energy planning [5]. Application of the smart energy system approach has been investigated in specific case studies which, among others, include: an analysis of the potential for energy autonomy through the use of renewable energy sources in the South West Region of Ireland and; the participation of small scale combined heat and power plants in Germany's secondary control balancing reserve as a means of integrating more intermittent renewable energy sources into the energy system [6–8].

Previous and current work has analysed how the implementation of a smart energy system could occur and, in the Danish context, what could impede this implementation, and what benefits could be delivered upon realisation. This article seeks to further this analysis by specifically addressing the issues of expanding wind power and reducing public subsidies for wind power producers. Moreover, it seeks to offer practical steps which could support the roll out of a smart energy system. With viability in mind, it is then the objective herein to link economic, social, and technical aspects which are essential to the realisation of smart energy systems and place them within the framework of a specific case study, one with the potential for success in this area.

In this article, the case of a community led renewable energy project is described. This is followed by a review of the current practices employed by the Danish Transmission Systems Operator (TSO) with regards to wind energy subsidies. Throughout the review, issues concerning the effectiveness of subsidies in promoting renewable energy usage are highlighted. A particular method for dealing with these issues, which is based on the integration of energy sectors, is then presented. The article concludes with a discussion on the validity of the analysis and its results and looks at how a community-based project could provide a testing bed for its deployment.

1.1. The case of Ærø and the Winds of Change project

The case presented herein takes its point of departure to be a possible community owned renewable energy and transport project located on the Danish island of Ærø. Ærø lies in the Baltic Sea and is part of the Southern Denmark region. The island is largely rural and has a relatively small number of inhabitants. In 2012, the population on Ærø, which covers an area of about 90 km^2, was around 6,600. Although the island's population density is only about 13% that of the average national value it is also the case that 75 of Denmark's 98 municipalities also have population densities which fall below the average [9]. The island is one of Denmark's poorest municipalities. Nonetheless, the people of the island have managed to implement successful community backed renewable energy projects. These include onshore wind turbines, district heating plants utilising biomass, and one of the world's largest solar power plants [10]. In this regard, Ærø can serve as a model of best practices which can be undertaken by poorer and more rural Danish communities with regards to renewable energy development.

Ærø has the stated goal of becoming 100% fossil fuel free [11]. Although the island has made significant progress in integrating renewable energy into its electricity and heating sectors, the transport sector currently relies almost entirely on fossil fuels [12]. In order for Ærø to achieve its stated goal, an electrified transport sector has been suggested. It has been concluded that the costs associated with such an electrification scheme could effectively be paid for with the revenue obtained from a community owned near shore wind farm project [13]. The socio-economic benefits of community owned near shore wind farms have been analysed in [14]. The study found that near shore turbines present less financial and technological risks than offshore instalments. While the former produce less than the latter, they do so with a lower generation cost. Further, near shore turbines lend themselves more easily to being implemented under community owned initiatives. While the same can be said about onshore as compared to near shore wind turbines, it is important to recognise the potential of near shore projects to provide an effective trade-off between generation cost and production, and between the potential for local ownership and the ability to satisfy Danish energy goals on a national scale.

The site proposed for Ærø's near shore wind farm has been investigated and the results detailed in Maxwell *et al*. The wind farm was modelled using WindPRO software. WindPRO is a module based software package which is used for the design and planning of wind power projects [15]. Using this model, it was determined that a

160 MW wind farm placed at the proposed site could operate for 4000 full load hours and deliver 660 GWh of electricity production per year [16]. The location of the site and its proximity to Ærø are displayed in Figure 1.

It is envisioned that the near shore wind farm be community owned. For this reason, shares from the wind farm are to be sold to members of the community with the intent that the revenue generated be put towards purchasing electric vehicles. A similar share offer will also be made to the entities responsible for the island's ferries and distribution grid. The overall effect would be that the revenue from the wind farm could be justly distributed as to provide benefits for the entire community not the least of which would be the electrification of Ærø's transport sector. The combined near shore wind farm and electrified transport vision has come to be known as the Winds of Change (WoC) project.

The concept of a 100% renewable energy island is not new to Denmark. Indeed, in this respect, Ærø shaes its goals with two other Danish island municipalities, Samsø and Bornholm. Currently, Samsø supplies 100% of its electricity needs from onshore and offshore wind turbines, most of which are community owned. Bornholm supplies 50% of its energy needs through renewable energy sources. Additionally, the island has been used as a testing ground for the development of an electrified trannsport and smart grid system [16]. The WoC project seeks to combine best practices from renewable energy and community owned projects such as these to deliver benefits both locally and nationally.

1.2. Subsidies and integrating energy sectors

Providing funds for individuals to purchase electric vehicles might effective deal with social barriers to the electrification of the transport sector. It has been shown in Baumann et al. that a Feed-In Tariff (FIT) of 9.4 c€ /kWh for the first 50,000 full load hours of production would enable the WoC project's near shore wind farm to provide the necessary funding for the electrified

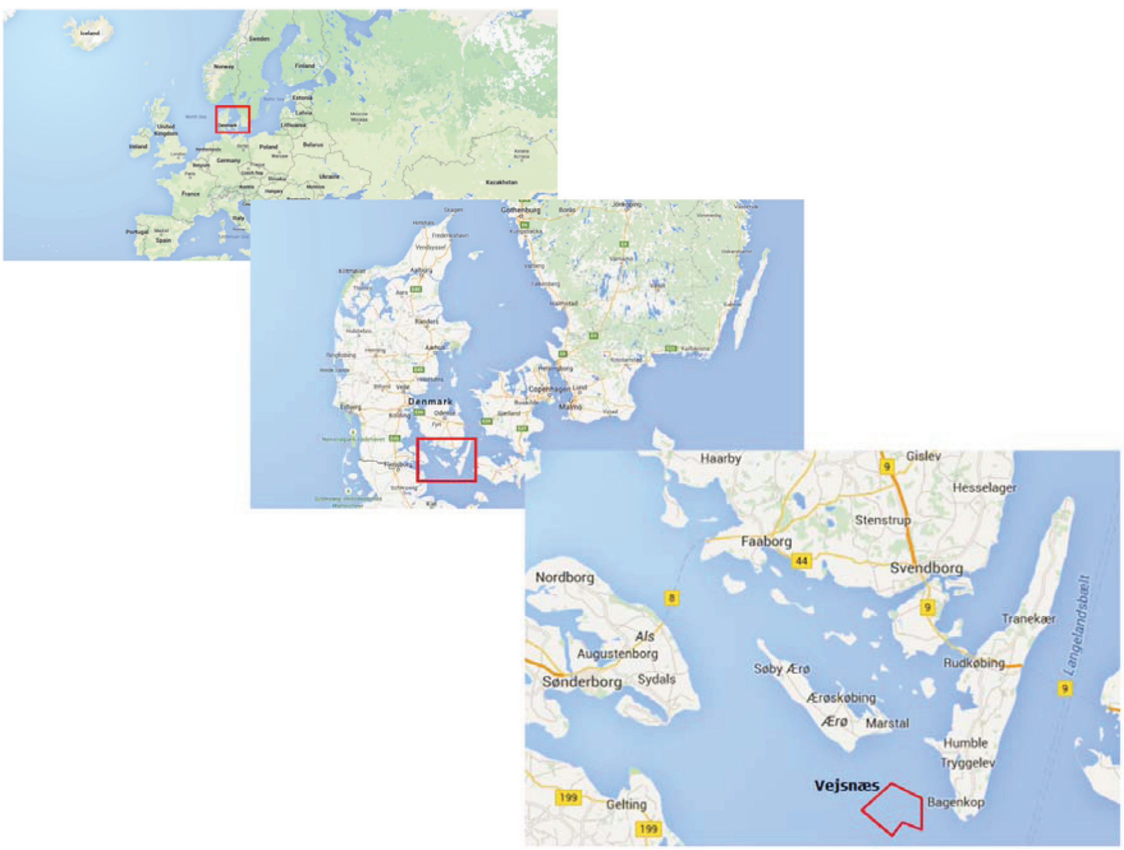

Figure 1: Location of case study relative to Denmark and Europe. The locations of the island of Ærø, its neighbour Langeland, and Vejsnæs, where the proposed wind farm is to be situated, are shown. The Vejsnæs site (shown in red) is one of several that was previously investigated by the Danish Energy Agency and deemed acceptable for near shore and offshore wind development [44].

transport vision after a 20 year period [13]. Such a FIT is granted by the TSO to wind granted by the TSO to wind farm projects that qualify for demonstration status. In order to obtain this status a project must provide the TSO with a worthwhile demonstration. Hence, it was recommended in the aforementioned report that the electrified transportation vision of the WoC project be scaled so that it might contribute to the integration of energy sectors on a larger level.

A demonstration of how a large scale roll out of electric vehicles would affect the national electrical grid has specific requirements. Firstly, this would constitute not only the implementation of electric vehicles themselves but also a charging infrastructure which allows the vehicles to interact with the electricity grid in an intelligent way, i.e. a smart grid. Secondly, in order for the electricity consumed by the electric vehicles to have a measurable impact on the national grid, a critical mass of consumption must be achieved. This would justify the implementation of a large number of fast charging stations. These stations would to be able to deliver significant amounts of electricity to and from electric vehicle batteries within a short amount of time and thus allow them to act on the regulating power market. This idea has already been proposed by the Danish TSO under the name EcoGrid Real Time Market [17].

Researchers with the EDISON project carried out an investigation on integrating electric vehicle batteries into a smart grid system [18]. A hypothetical scenario involving 2,000 electric vehicles, each with a maximum charging capacity of 11 kW (230 V using a 3 phase charger at 16 A), was analysed. It was found that for a 60 kV grid system, a 20% electric vehicle penetration (i.e. 20% of the cars charging simultaneously at any particular time) would result in the transformers being overloaded [19]. It has been proposed in Baumann *et al.* that a total of 7,500 electric vehicles be implemented as part of the WoC project's electric transportation vision. A fast charging system would require around 22 kW of power (230 V 3 phase at 32 A) [20]. It is envisioned that in order to make a significant impact on the transmission grid and the regulating power market, at least 5,000 of the proposed 7,500 electric vehicles, or around 67%, should be plugged in at any given time. A study by the EDISON project which looked at driving patterns in Denmark concluded that over 90% of cars are parked at any given time [21]. Therefore the assumption that 67% of electric vehicles would be connected to the grid at any given moment is valid. Having this many cars connected would create a load of 110 MW. This load is comparable to the average imbalance (surplus or deficit) which Denmark's transmission system experiences on an hourly basis [22]. Therefore, 5,000 electric vehicles charging at a given hour could be used by the TSO as regulating capacity and thus make a significant impact on the transmission grid. To be sure, this would require significant improvement of the local grid system on Ærø, a fact which has been taken into consideration by the economic analysis carried out in [13].

1.3. The current state of wind power subsidies

As mentioned, the WoC project seeks to obtain subsidies, in the form of a FIT, from the Danish TSO. However, there has been a lot of political discourse on the extent of financial support for FIT payments to wind farms and a recent move by political parties to lower the Public Service Obligation (PSO) tariff [23]. The PSO, by providing financial support on top of the market price to wind farm and biomass developers, is used as a means of promoting electricity production from renewable sources [24]. Currently, all electricity consumers are charged the PSO tariff on their electricity bill as the implementation of renewables into the energy system is seen as benefitting the whole of Danish society.

Subsidies paid to wind farm operators depend on the procedure utilised when applying for tender from the TSO. Wind farms released for tender by the government are entitled to a payment equal with the lowest offer made by one of the participating bidders. In such cases, the subsidies paid by the TSO would be equal to the difference between the fixed price per kWh and the electricity market price for a given amount of full load hours. Two recent offshore developments, Horns Rev II and Rødsand II, have negotiated FIT's of 7 c€/kWh and 8.4 c€/kWh respectively. In both cases this applies to the first 50,000 full load hours of operation [25] [26]. Moreover, the Anholt offshore wind farm, which at 400 MW has double the capacity of the other two offshore developments, has received a FIT of 14 c€/kWh for its first 50,000 full load hours of operation [27]. Using the average electricity spot market price for wind in eastern Denmark in 2012, the total subsidies paid to these three wind farms will amount to 1.8 billion € [28].

Subsides, such as the PSO tariff, are intended to help renewable energy producer who are not able to payback their investment under current market conditions. The PSO is charged to the electricity bill of all consumers, meaning that with every new wind farm installed the PSO increases and so does the electricity bill of the end-users. In recent months the Danish political parties Venstre (Left Liberal Party), Det Konservative Folkeparti (Conservative People's Party) and Dansk Folkeparti (Danish People's Party) have indicated a preference for policy eliminating the PSO [29]. This political debate is growing in intensity, and the support for wind projects is waning due to the perceived social burden. In elections held in June 2015 the centre-right conservative "blue bloc" has won a majority of parliamentary seats. This change in government may likely have implications for public spending in the renewable energy sector in Denmark [30].

2. Lowering PSO payments.

Granting subsidies to renewable energy producers is not a novel concept. Between the years 2001 to 2005, the Danish Government allotted an annual amount of 228 to 376 million € to wind farms [31]. The issue is that these subsidies tend to stay within the sectors to which they are granted and thus the implementation of integrated energy solutions is hindered. Hvelplund, et. al report on one relevant case in which the increase in solar power reduced peak load prices on the electricity market by about 10%. However, the cost savings were not passed on to the consumer, even though they were the ones forced to pay an increased PSO due to the increase of renewable energy in the system. [32]. The reason for this is that even though peak load prices were reduced, the solar power producers still required a minimal per kWh payment to continue operation. The PSO acts to insure that this minimal payment can be made. However the PSO is allocated to individual energy sectors (electricity, heating, transportation) separately and does not insure a socioeconomic efficient integration of energy sectors. There is therefore a major defect in the way subsidies are allocated.

2.1. Using subsidies across sectors

Strategies which utilises subsidies across energy sectors may help to reduce the burden of providing public funds for renewable energy projects. Further, this could allow those funds which are provided to have a greater effect in transitioning energy sectors away from fossil fuels. Implementing these strategies at a local level could also aid in the financial development of underprivileged communities.

The upcoming plans of the TSO stipulate the implementation of 1.45 GW of offshore wind power into the energy system before the year 2020 [33]. This implementation will likely increase the PSO payment charged to consumers. Currently, the majority of offshore developments in Denmark are owned by partly state-owned, partly private utilities. These companies tend to demand a higher return on their investments than smaller, locally-run businesses. [14]. The power producers demand for profit will surely influence their expectations as to what level of FIT they should receive. It could prove difficult for the TSO to relieve the financial burden of individual energy consumers if they wish to have the current large offshore wind players implement the planned 1.45 GW. Increasing the consumption of electricity from fluctuating renewable energy sources through the use of electric based demand side units in the transportation and heating sectors may be a means of resolving this difficulty.

Nord Pool Spot, the electricity market under which Denmark and other neighbouring countries operate, has a supply capacity curve which follows a so-called merit order, depicted graphically in Figure 2. The merit order is a market mechanism by which electricity producers are automatically ranked in terms of the price of the electricity they sell, so that those which submit the lowest price bid to the market are the first to meet consumer demand. The TSO purchases electricity and regulating services on an hourly basis and the final electricity price at a given hour is determined by the producer with the highest price bid whose electricity was demanded [34]. The point on the merit order graph where the two curves of demand and supply intersect determines the electricity price for consumers. Due to the merit order mechanism, if demand remains fixed, the market price is reduced when additional wind power, which has low marginal electricity production costs, is added to an energy system. This may lead to the situation where the market price for electricity is too low to cover the cost margins of electricity producers. A subsidy might then be provided to the producers to cover the additional costs. Of course the motivation to bring renewable energy producers on line is to reduce the amount of energy from fossil fuel which is consumed. It seems logical then that as more renewable energy units are implemented that the consumption of the energy they produce also be increased. In this way, the shift in the supply curve of the merit order system would be followed by a corresponding shift in the demand curve.

However, it is important to take into account the fluctuating nature of renewable energy sources. Wind

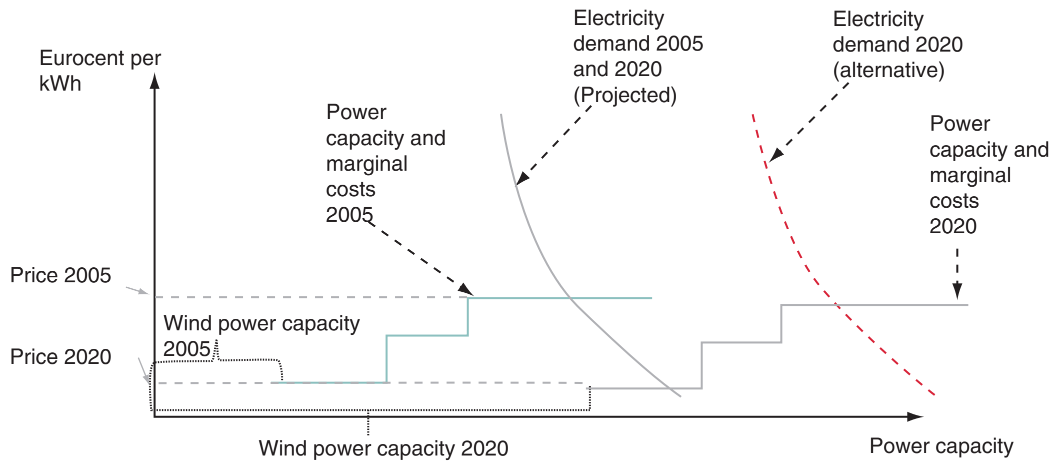

Figure 2: The merit order system. As projected for the year 2020, wind power capacity increases, and demand remains constant, so that the difference between the price which the TSO pays to wind power producers and the price which the TSO charges consumers grows. Consequently, wind power producers rely more heavily on PSO payments. Alternatively, electricity demand could increase along with the increasing wind capacity. This would ensure that the wind power producers receive an appropriate payment without having to rely on subsidies. Figure taken from [32] (altered).

resources by their nature deliver a fluctuating supply of electricity, the amount available being greater at times when the wind is blowing and less at times when it is not. Therefore, the consumption of this electricity must also be flexible. This implies that electricity will have to be stored or converted in some way for use when the production units are not able to meet demand. Electric vehicles and heating plants run on electricity can provide a means of storing the electricity from fluctuating renewable energy sources. The integration of the electricity, heating, and transportation sectors in this manner would reduce, and may in the long term eliminate, the need for PSO payments. Although the value of electricity would increase if it was used in all three energy sectors, due to, for example, the higher conversion efficiencies of electric as compared to fossil fuel units, it is likely that the overall energy costs for consumers would be reduced. To see how increased electricity consumption under a smart and integrated energy system might affect the electricity costs of the Danish energy system, an analysis is conducted which utilises historical consumption, production, and electricity price data to model a possible smart energy system.

2.2. Energy demand on Ærø and in Denmark

An analysis of the energy consumption by sector on Ærø was made in Jakubicka *et al*. The analysis shows that the energy consumption in the transportation and heating sectors on the island far exceed that of the electricity sector [12]. A total of around 159 GWh of energy is consumed annually on Ærø. Of this, 32% is consumed in the transportation sector, 47% in the heating sector, and 21% in the electricity sector. Considering the fact that the vast majority of the heat production units on the island already run on energy from renewable sources, plans for increased electricity consumption there would likely focus more on the transportation sector. This situation is unique on Ærø however, and plans for increasing electricity consumption in other Danish municipalities would likely involve the heating sector as well. It is important to note here that Denmark as a whole has taken significant steps towards increasing the use of renewable fuels (biomass and waste) in its district heating plants and that the country is a world leader in the use of Combined Heat and Power Plants (CHP) which greatly improves energy efficiency. Nevertheless, the increase in use of renewable energy in the country's heating sector has been slower than that in the electricity sector. During the period from 2002 to 2013, in relative terms (percentage of total) electricity production from renewable sources has tripled while heat production from renewables has increased by slightly over 50%. On the other hand, renewables make up almost half of the fuel used for heat production and only about a third of that for electricity production. [35]. However, one should not only take into account the quantity but the quality of these fuels as well. In this regard, it could be argued that the sustainability of the renewables used in heat production, the vast majority of which are biomass, is questionable. In any case, it seems that there is potential to increase the use of renewable based electricity throughout Denmark's energy sectors.

Looking at the transportation and heat sectors, it is important to keep in mind that electric and fossil fuel based units have different efficiencies, and that efficiency values play a large part in determining the amount of energy needed to run those units. Electric automobiles, for example, are in general 3 to 4 times as efficient as internal combustion engine cars. So while the latter might use 0.1 L of petrol (about 1 kWh) to drive a distance of 1 km, the former might use 0.34 kWh of electricity for the same trip. [36] [37]. Similarly electric heat pumps may have a Coefficient of Performance (COP) of 3 or 4, meaning that they produce 3 to 4 units of heat for every unit of electricity taken in [38].

Using the efficiency factor, one may determine a probable value for the amount by which electricity consumption on Ærø would increase if the transportation sector there was electrified:

$$\%_{increase} = \frac{50.9GWh * x_{efficiency}}{33.4GWh} * 100 = 51.8\% \qquad (1)$$

where 50.9 GWh and 33.4 GWh are the amounts of energy currently used in the transportation and electricity sectors respectively, and $x_{efficiency}$ is the efficiency ratio between electric vehicles and combustion cars, namely 34%. It should be noted that agricultural equipment and planes are left out of the energy consumption calculation for Ærø's transportation sector.

Achieving high levels of electricity consumption, and specifically consumption of electricity from renewable sources, is necessary if, as the TSO plans, more wind power capacity is to be brought on line. As described in [3], the largest contributor to this increase could be synthetic fuels. This means of stored electricity would also be essential for the demand side flexibility required of a smart and integrated energy system. The matter of storing electricity is important, and although synthetic fuels would likely play an important role in this regard, this article is more concerned with methods which may be employed by individual consumers and thus concentrates on electric vehicles and heat pumps.

2.3. Roll-out of eletrical vehicles and heating units

While identifying how electricity from fluctuating renewable sources may be utilised is certainly important, the purpose of the analysis here is to gain insight on how increased electricity consumption could affect the market conditions under which those renewable energy producers operate. Nevertheless, it is interesting to imagine how a national move towards flexible electricity consumption could occur, and what role the WoC project could play in this development. One possibility could be that a successful implantation of WoC acts as a catalyst for a country wide deployment of electric vehicles, heat pumps, and other demand side electrically powered units. For the purposes of the following analysis, it is assumed that the WoC project is implemented in 2015 and proved to be successful at integrating energy sectors and reducing PSO payments on Ærø within its first 5 years of operation. After this time, beginning in 2020, the effect of increased consumption starts to make an impact on the national spot market price for electricity. This occurs slowly yet steadily as more electric based consumption units are brought online throughout Denmark. On the supply side, it is assumed that the TSO's planned 1.45 GW of offshore wind power is implemented in 2017. Given this imagined narrative, a timeline is constructed on which further analysis can be constructed.

3. Increasing electricity consumption

On the basis of the assumptions given above, an investigation is carried out that analyses the influence of increased electricity consumption on a national level and specifically the market price of electricity. Figure 3 shows a flow chart listing the four major steps of the analysis.

The investigation begins by looking at historical data in order to find a correlation between electricity consumption and price in Denmark. The data used in the analysis is taken from the Danish TSO's registry of market data. For the correlation study, hourly values for DK-West gross consumption (Western Danish consumption including transmission loss) and DK-West Elspot price for the years 2002–2013 are analysed. Using the correlation between the two variables, a prediction is made as to what the electricity price might look like if electricity consumption is increased. Apart from these, a number of other factors, including primary production (production form central power stations), local production (production from local CHP's), wind power production (including on and off shore), and physical exchange on transmission lines (between Denmark and its neighbours Norway, Sweden, and Germany), are examined to further analyse the relative importance of electricity consumption in determining price. The data for these factors is also obtained from the TSO's registry.

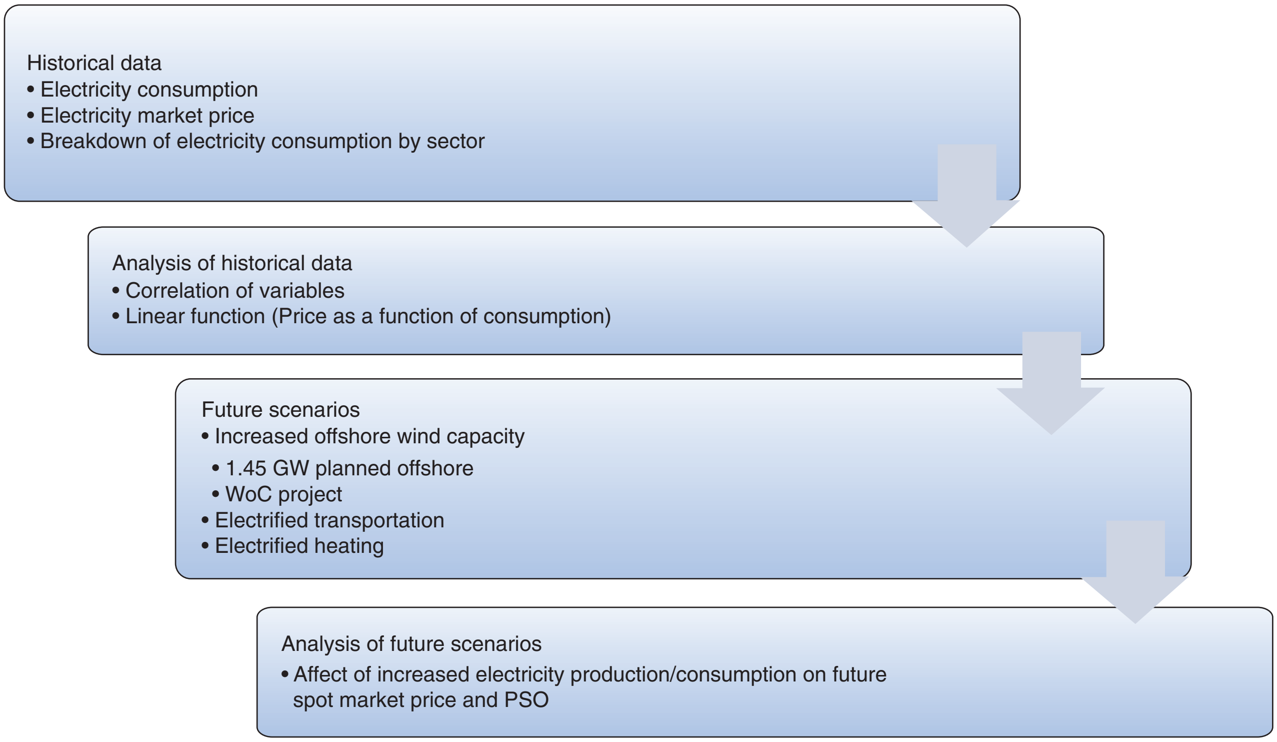

Figure 3: Flow chart of the analysis documented in the article.

In the next part of the investigation, a comparison is made between the overall costs which the TSO could incur due to their proposed implementation of 1.45 GW of offshore wind capacity and the costs of implementing both the proposed 1.45 GW and the WoC project under the condition of increased electricity consumption. It is assumed that the electricity price which would be paid to the producers of the new 1.45 GW of capacity would be comparable to the FITs which have been granted to recent offshore developments. The period for which the FIT is applied is similarly determined. The WoC wind farm is assumed to receive the FIT applied to projects which are granted demonstration status by the TSO. The results of this investigation are tabulated and discussed in the following sections.

3.1. Electricity price and electricity consumption

As stated, the analysis seeks to evaluate the effect of added flexible consumption of electricity on the market price (Elspot price). Data about national electricity consumption and price behaviour is used to carry out the analysis. Specifically, hourly data of the above variables for the region DK-West given over a 12 year period from 2002 and 2013 was provided by the Danish TSO through their website, energinet.dk. In analysing the similarities from year to year, it was observed that for electricity consumption, the mean of the standard deviation (σ) is about 12% of the average value and that 60% of values fall into the 1σ category. For wind production the mean of the σ is about 85% of the average value and 67% of values fall within 1σ. These numbers reflect the fact that while more wind capacity has been added into the system, there has not been a corresponding increase in consumption.

In order to determine the effect of increased electricity consumption on the spot market price, it is necessary to evaluate the historical relationship between these two factors. Towards this end, hourly values for consumption and price for the years 2002 to 2013 was obtained. This data was in turn used to create a model year based on the hourly median values. The model year data was then used to evaluate the linear correlation between the two factors in question. The results of this analysis are shown in Figure 4. To be sure, the figure shows the linear correlation between median values. Further, the data points are constricted to those which fall within 1σ of the mean. This includes about 60% of consumption values, as stated, and around 90% of price values. In this way, the effect of outliers in determining linearity is reduced compared with an analysis which includes the entire

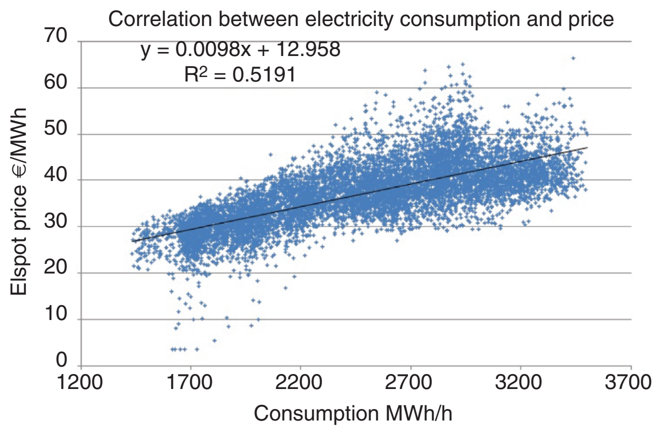

Figure 4: Correlation between electricity consumption and market price (Elspot) in Denmark. Median values are taken of the hourly price and consumption values for the years 2002 to 2013. Using the linear relationship found here, the effect of increased consumption on the electricity market price may be determined.

range of values and uses averages for central tendency. In any case, it is interesting to note that these outliers in the data set are due to low wind production, power outages, and poor electricity flow between the interconnectors in the market regions (e.g. Denmark and Germany) and although some of these issues have been resolved through the use of market coupling across borders of European countries, times of reduced electricity production from low cost renewable energy sources may still lead to the use of more expensive energy systems such as coal fired power plants. [39].

The correlation shown in Figure 4 may be understood as the result of an increased wind power share and a variation in electricity prices between day and night hours due to electricity consumption differences therein (the former generating higher consumption than the latter). However, it should also be noted that the above correlation appears in the period 2002 to 2013 in which the annual electricity consumption had been for all due purposes constant. Therefore, the correlation factor is not influenced by generally increased or decreased electricity consumption over time but only by the hourly variation in consumption.

In the graph, the data is sorted according to the increasing consumption. The relationship between the two variables is given by the following linear regression function:

$$y = 0.0098x + 12.958 \quad (2)$$

Here, y refers to the electricity price and x to electricity consumption. The coefficient of determination (R^2) for the statistical analysis is about 0.52. It is important to remember that the R^2 is a measure of variance, specifically the amount of variance in one variable which may be determined using the other variable. When a data set has been adjusted to account for variance, the minimum value for R^2, where by an accurate determination of variance may be drawn from the linear analysis, decreases [40]. In the analysis here, in order to account for yearly variance in the data, median values are used to determine linearity. To gain further insight on the R^2 value, the correlation between price and consumption is examined for each year (2002 -2013) separately. It is found that the hourly price values obtained by use of the linear function (this being calculated using the same method applied to the multi-year analysis) have a median variance from the real values of about 15%.. Further, in general around 50% of the hourly values fall below the respective error for a given year. It may therefore be said that the linear model provided here can determine the variance in electricity price given consumption value within a 15% error at a confidence level of 50%. This finding reinforces the significance of the R^2 value which has been found, namely in that the latter implies that 52% of the variance in electricity price may be explained by electricity consumption. One may further look at the linear correlation coefficient value, R, which in this case is 0.72 and indicates a generally strong and positive correlation between the measured variables. While the correlation given above may not be an especially accurate method of determining future electricity prices, it is acceptable for this investigation given that the focus here is on the relationship between price and consumption and not the two components individually. Further, analysing this relationship over a 12 year period provides a suitable range so that fluctuations in the market which might affect the price/consumption relationship can be considered.

To evaluate the link between electricity demand and market price, consumption values are altered so that both the average electricity price across all hours of the day is increased and the rate of demand throughout the day (and therefore the price) levels out. To achieve this, the largest increase in demand should occur during off peak hours, these being the hours 1:00 through 7:00, and 21:00 through 24:00. These hours are chosen due to a variety of reasons. For one, there is generally less electricity consumption occurring during these hours (on average, about 2/3 of that which is consumed during the hours of 8:00–20:00). Correspondingly, the electricity price is lower. Because the aim of the strategy proposed here is to increase the electricity price so that wind farm operators rely less on subsidies, it makes sense to target the hours when electricity price is lowest. Secondly, there is a greater likelihood that vehicles are stationary during the off peak hours. Consequently, electric vehicle batteries would be available for use on the regulating market during these hours. Again, consumption during off peak hours is increased with the twin goals of increasing the average Elspot price across all hours and levelling out the rate of demand throughout the day. Creating a relatively stable electricity price throughout the day could be seen as a way of guarding against the loss of social welfare which wind power experiences during times of low consumer demand [41].

Figure 5 gives a comparison of two Elspot price curves: one based on current consumption values (blue) and one on a possible increased consumption scenario (red). To generate the blue curve, the average of the electricity consumption values for each hour of the year across the years 2002–2013 is inputted into Equation 2 to generate a corresponding average current Elspot price. The horizontal bars at each point along the x axis in Figure 5 reflect the range of values for the given hour of the day. For the red curve, an average is taken of the average electricity consumption values for the off peak hours. These values are then multiplied by the 51.8% increase value found in Equation 1 so as to determine an upper limit for the new increased consumption values. Given this restraint, the consumption values for the off peak hours are manipulated so as to reach the twin goals mentioned above. Having the aim of raising the average price and levelling out the demand throughout the day implies that for those off peak hours where price is lowest in the blue curve, the increase in consumption will more closely approach the upper limit in the red curve. Simply said, night time electricity consumption is increased to daytime levels so as to generate daytime prices during night hours.

As shown in Figure 5, the electricity market price increases for the hours in which consumption was increased. The fact that the analysis shows market price increasing with increased consumption is logical, given that the linear relationship between the two variables was used to calculate these new results. The red curve shown in Figure 5 is used as a means of visualising what an increased average Elspot price might look like, and not necessarily to determine a particular value. The following section will examine the possible consequences which an increased consumption scenario might have on the feasibility of new wind power projects (including the WoC project) and how this might in turn affect PSO payments.

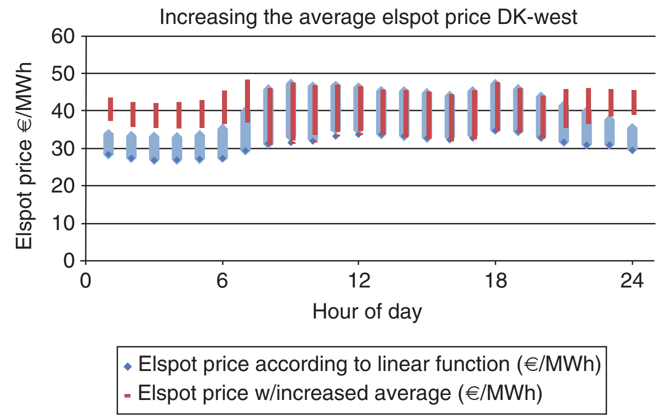

Figure 5: Effect of increased consumption on market price (Elspot). The linear relationship given in Equation 2 is used to determine the electricity price for each hour of the day. The data series in blue reflects price trends under current consumption behaviour. In the red data series, consumption has been increased for the off peak hours (1:00 – 6:00, 21:00 – 24:00).

3.2. Electrified transport and subsidy payments

The following section analyses the potential economic impact of having an increased average electricity market price. Given the TSO's wind power ambitions and the push by the Danish Government to lower or eliminate PSO payments, there is motivation to find a method by which wind farms can operate with less of a reliance on subsidies. The method suggested herein involves increasing electricity consumption so as to reduce the amount of money that the TSO has to pay to wind farms operators.

The analysis starts by calculating the payments which have to be made by the TSO over the next years to the wind power producers providing the planned 1.45 GW. Using the prices negotiated in the Horns Rev II, Rødsand II, and Anholt cases as an indication, it is assumed that the TSO pays a subsidy which guarantees a price of around 9.4 c€/kWh for at least 50,000 full load hours to the wind farms making up the planned 1.45 GW. How much money this actually entails depends on the spot market price. The average FIT negotiated in the three given cases is about 9.8 c€/kWh. The slightly lower value is instead used to make a direct comparison with the demonstration status FIT sought by WoC.

Predictions of the spot market price are somewhat uncertain due to the complexities of the market and are usually based on forecasting of historical trends and take into account planned future development such as new installed capacity. Although uncertain it is nevertheless useful to examine the TSO's electricity price forecast. Figure 6 depicts the TSO's projection (red line) and compares this with a simple extrapolation based on the historical data (blue line). The 50,000 full load hours in which the analysis conducted here takes place occurs some time during the years 2015 – 2029. As shown, the deviation between the two projections for the first half of this time period is quite large, with the extrapolation value for year 2016 being about 50% greater than the TSO prediction. The values then seem to more or less coalesce after 2019 but begin to once again deviate towards the end of the 15 year period in question. The TSO prediction will suffice for the purposes here. To reiterate however, the lower the spot market price, the higher the subsidy payment.

Given the subsidy payment scheme described above, and assuming that all the wind farms in the 1.45 GW plan produce an average 3,800 full load hours per year, the first of three scenarios is constructed (Scenario 1 in Table 1). Scenario 1, being based on the TSO's current proposal, will act as a reference by which the next two scenarios may be compared. In this reference scenario, it is assumed that the 1.45 GW of offshore wind power is implemented in 2015 and that a FIT is paid to the wind producers for the first 50,000 full load hours of production. Under these conditions, the TSO pays around 3.01 billion € in subsidies for the new wind farms during their first 13 years of production. Given that the capacity factors for Denmark's newest offshore wind farms, Anholt, Rødsand II, and Horns Rev II, are 46.7%, 42%, and 48% respectively, the assumption of 3800 full load hours is reasonable [37]. It is important to note that [27] gives a ratio of about 3.9 between offshore wind production and installed capacity for the year 2011. The ratio for the WoC near shore wind farm found in [14] is about 4.1. In light of these documented values, assuming 3800 full load hours for the TSO's planned offshore wind implementations is somewhat conservative.

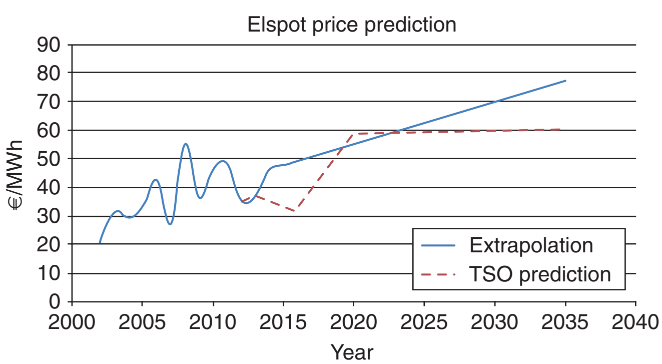

Figure 6: Two predictions for the future of the Elspot electricity market. The blue line represents an extrapolation based on median annual values for past years. The red line represents the values given by Energinet.dk in [45]. The TSO's prediction is based on a combination of forward prices, for the short term, and its own energy models for the longer term.

The first scenario is compared to one where electricity consumption is increased so as to raise the average Elspot price across all hours of the day, as described in the previous section. The increased consumption in this new scenario (Scenario 2 in Table 1) is motivated, in part, by the implementation of the WoC demonstration project. The WoC project's near shore wind farm seeks to receive a FIT of 9.4 c€/kWh for the first 50,000 full load hours of production. In Scenario 2, it is assumed that the WoC wind farm is implemented in 2015. Using the same assumptions regarding the development of the market price used to analyse the TSO's 1.45 GW plan in Scenario 1, the WoC project, if it were granted the above FIT, would receive a total payment of about 356 million € over 13 years.

Scenario 2 assumes that changes in consumption occur due to electrification of the transportation sector throughout the whole of Denmark. Therefore the consumption increase value given in Equation 1 is taken into account. The 51.8% is used as an upper limit for the value which consumption can be increased at any given hour. This constraint reflects the fact that the energy use on Ærø mirrors that in Copenhagen and presumably the rest of Denmark. As the 51.8% value was arrived at by assuming that all private transportation on the island is electrified, it would seem unlikely that a higher value could be arrived at when the whole of Denmark is considered. At the same time, an added restriction is placed that new hourly electricity consumption values should not go beyond the maximum value (average maximum value in a given hour) taken from historical data. This means that the increase which occurs during hours of traditionally low electricity consumption (i.e. night hours) will not go over the current maximum which occurs during hours of historically high consumption. As mentioned, increasing consumption in this way may help to safeguard social welfare. Given

Table 1: Three scenarios have been analysed in order to determine the feasibility of utilising renewable electricity subsidies in integrating energy sectors. The table lists the three scenarios, the conditions applied for each, and their respective outcomes.

Scenario	Conditions	Outcome
TSO Proposal	• Implementation of 1.45 GW of new offshore wind capacity. • Electricity price follows prediction of [45].	• TSO pays a total of 3.01 billion € during first 13 years of new offshore production
TSO Proposal and WoC with Electrified Transport	• Implementation of 1.45 GW of new offshore capacity and WoC project (160 MW). • Electricity spot market price increases due to electrification of transport sector	• TSO pays 2.66 billion € for 1.45 GW during first 13 years of production • WoC receives 356 million € for first 13 years of production • TSO saves 343 million € on its planned 1.45 GW
TSO Proposal and WoC with Electrified Transport and Heat	• Implementation of 1.45 GW of new offshore capacity and WoC project (160 MW). • Electricity spot market price increases due to electrification of transportation and heating sectors.	• TSO pays 2.60 billion € for 1.45 GW during first 13 years of production • WoC receives 351 million € for first 13 years of production • TSO saves 410 million € on its planned 1.45 GW

these assumptions, Scenario 2 predicts that the average spot market price will increase by about 0.5 c€/kWh (from 3.9 to 4.4 c€/kWh).

The increase in spot market price will most probably occur gradually, as it will follow the roll out of electric vehicles on a national scale. Therefore the full 0.5 c€/kWh increase is assumed to be realised by 2050, and is achieved by a progressive increase which begins in 2020. Specifically, the electricity price increases by 3% of the total stated increase every year as compared to the previous year, reaching the full 0.5 c€/kWh increase in 2050. This increase in turn leads to a decrease in the PSO payments which are due to the TSO's planned 1.45 GW of offshore wind. In Scenario 2, the planned offshore capacity is implemented in 2017 as opposed to 2015. In terms of the timeline narrative, this delay could allow for some preliminary analysis of the effectiveness of the WoC implementation strategy. The producers of the 1.45 GW are still granted FIT for 50,000 full load hours. The total PSO payments are then seen to decrease by around 11% (343 million €) as compared to Scenario 1.

A comparison is made between the Scenarios 1 and 2. The results of this analysis show that in the second case, while the TSO does experience savings due to an increased average spot market price, these savings would not cover the costs of implementing both the 1.45 GW and WoC projects. The TSO would have to pay around 12.7 million € over 15 years for WoC in addition to the 2.66 billion € they will pay for the planned 1.45 GW, with the obvious consequence on consumers obligated to pay PSO.

3.3. Electrifying transportation and heating sectors

The previous analysis has shown that a scenario where an electrified transportation sector results in increased electricity consumption may not necessarily justify subsidising the WoC project. Therefore a third scenario (Scenario 3 in Table 1) where both the transportation and heating sectors are electrified is now investigated. As mentioned previously, plans to increase electricity consumption to a level where wind farm operators could reduce their reliance on government subsidies would likely have to involve electrification initiatives in both sectors. This is also likely what would be needed in terms of implementing smart energy systems.

As explained previously, the relative breakdown of energy consumption by sector on Ærø follows closely that of Copenhagen and likely Denmark in general. For both locations electrifying the transport sector would, as shown in Equation 1, increase electricity consumption by around 51.8%. Using the same calculation and a COP of 3 for electric heating units, electrifying the heating sector would increase electricity consumption by around 74.6%. In Scenario 2, the method of raising the average electricity price affected primarily off peak hours (01:00 – 07:00, 21:00 – 24:00). In Scenario 3 that previous condition is kept and in addition the electricity consumption during winter months (December, January, and February) is increased across all hours by 74.6%. This latter increase is due to transformations in the heating sector. To be sure, large scale heat pumps which run on electricity from renewable sources could be used to replace (at least in part) traditional base load heating providers, such as coal fired and CHP plants. If so, the heat pumps could run year long and not just during winter months. This possibility has been explored in [42]. The authors of that paper suggest that using heat pumps for base load might be an effective means of creating more flexibility in the demand side of the Danish energy system. This is much in line with the smart energy systems approach discussed in [1].

The increase in electricity consumption due to the combination of electrified heating during winter months and electrified transportation results in an average spot market price of about 5 c€/kWh (an increase of 0.6 c€/kWh from the value found in Scenario 2 and of 1.1 c€/kWh from that in the reference scenario). Of course, these new conditions imply that the Elspot price will be significantly greater during winter months than in the rest of the year. Whether this will affect social welfare positively depends partly on the effectiveness of thermal storage. While the need for heating during winter months is certainly without question, the flexibility of this demand is possible with seasonal thermal energy storage systems. However, for the purposes here, it is assumed that the heat demand (and thus the electricity consumed in the electrified heating scheme) does increase during winter months unaffected by storage options.

Scenario 3 predicts that PSO payments for the TSO's planned 1.45 GW of offshore decrease by around 14% (410 million €) for the 15 years of production investigated in Scenario 2. These savings allow the TSO to finance the WoC project and save an additional 59.5 million € over the given timeframe.

3.4. The viability of locally integrated nearshore wind farms

The results of the analysis shows that under certain conditions the TSO can both reduce the amount of subsidies it would otherwise pay for its planned 1.45 GW of offshore wind and also feasibly grant the suggested FIT to the WoC project. However these may not be the exact conditions initially envisioned by the WoC project which sought to focus on the electrification of the transportation sector. As described, the WoC project seeks to direct profits from its proposed near shore wind farm to individuals who wish to purchase electric vehicles. It is thus creating an economic motivation for local communities to install new, flexible electricity consuming units. This will in turn help to create the demand side flexibility advocated by the smart energy systems approach. The preceding analysis has found that to pay for the WoC project and at the same time ease the burden of electricity customers who make PSO payments, the spot market price will have to increase. This increase may have to come from electrifying both the transportation and heating sectors. It might be possible for the WoC project, or a similar initiative, to provide an economic incentive for individuals to purchase electric heating units. Unfortunately, this will likely increase the costs of the project if the electrified transportation budget remains as is. Nonetheless, it is important to note that projects which concentrate only on electrifying the transport sector may still carry an intrinsic value as they could be necessary in order to demonstrate certain aspects of a flexible and integrated electricity infrastructure.

It should be made clear that the preceding analysis has not taken into account economic benefits which could come from the WoC project's environmental and social impacts. Indeed the project has the potential to increase employment, act against climate change, create new opportunities for innovation and education, and strengthen community bonds. It could be that a more in depth analysis reveals these benefits make up for the costs incurred in the electrified transport scenario. Nonetheless, if the Danish Government were to implement the increased consumption plan as suggested by the WoC project, it is very likely that energy consumers would experience lower overall energy costs. To quantify this, an analysis is made comparing the costs of combustion vehicles with that of electric vehicles. The analysis is based on historical market price values for petrol and electricity in Denmark and extrapolates this data to predict what prices might look like for the next 10 years. Average fuel economy values for the combustion and electric vehicles are taken from [37] and [36] respectively. The results of this analysis are given in Figure 7. It is important to note that while future fuel costs could vary largely from what is predicted here, the fact that there is such a large difference between electricity and petrol prices (even when increased electricity consumption is taken into account) allows for a certain degree of assuredness in stating that increasing the use of electricity in the transport sector would lower the total energy costs of consumers.

In the heating sector, energy costs here could also likely be reduced by increasing the use of electric units such as heat pumps. Previous studies have drawn attention to the role of heat pumps in smart energy systems [3, 42]. However electric heating units have long suffered under unsupportive tax policies in

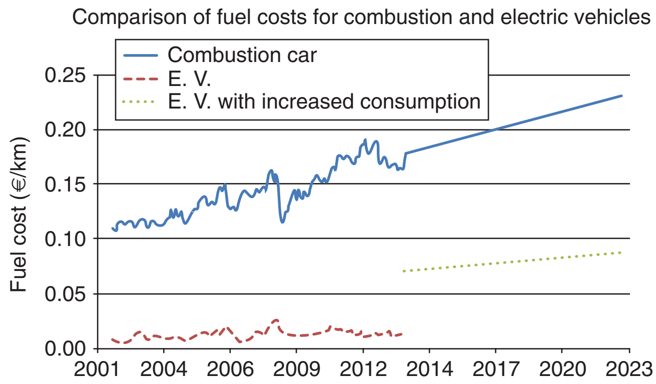

Figure 7: Comparison of fuel costs for combustion and electric vehicles. As can be seen by the historical data, while electricity costs have been low and relatively stable, petrol prices have risen from 10 times to over 15 times that of electricity. Extrapolating the data and using Equation 2, a prediction is made of the fuel costs for an electric vehicle under the situation of increased electricity consumption. The green line represents what an increase of 450% in the electricity price (more than 6 times that which was projected in Scenario 3) would look like. As shown, even using this high estimate for the increase in electricity price, electric vehicles would still remain more affordable than combustion cars.

Denmark. While legislation which amends these policies in favour of electric heating has been introduced, the landscape is still somewhat unwelcoming [32]. A recent report by the Danish District Heating Association suggests that both reconsidering how heat pumps are taxed and lowering PSO payments could open up the market for these units and help promote them among district heating producers [43]. With regards to the latter, integrating energy sectors could be beneficial.

The issue of consumer motivation is essential to the community based ownership structure advocated by the WoC project and also to the proper functioning of a flexible and integrated smart energy system. In the case of Ærø, the benefits of replacing traditional transportation units with their electrically powered counterparts will have to be made clear to the individuals who will purchase shares from the nearshore wind farm beforehand so as to insure that revenue will indeed be directed towards the envisioned smart energy initiatives. After the electric vehicles are purchased, the consumers will have to be mindful of the fact that the burden of flexibility within the energy system will be transferred from the supply to the demand side. This will likely require a change in consumption habits. The role of the consumer would be equally important in a similar situation involving electric heating units. This implies that the benefits incurred would be more strongly related to consumer activity under a smart energy system than under the current fossil fuel based system. In light of this, future studies might do well to correlate cost benefit analysis for individual energy consumption units with that of supply side units such as the WoC project's nearshore wind farm to determine whether the payback period for both fall within the same time frame.

4. Discussion and Conclusions

The preceding analysis has shown how increasing electricity consumption, and specifically during night hours, can reduce the amount of subsidies that the TSO pays to wind power producers. Increasing electricity consumption requires that the transportation and heating sectors become less reliant on fossil fuels and utilise more electricity from renewable energy sources such as wind. One effective method to promote the implementation of electric based units in these sectors is to reduce the amount that consumers pay for them. This could be done by using government subsidies for wind projects across energy sectors. For example, a portion of the revenue from subsidised wind farms could be transferred to consumers of electric vehicles. While this would help to increase the number of electric vehicles on the road it would also increase the amount of electricity being consumed during off peak hours, thereby lowering the PSO payments that the same consumers would have to pay on their electricity bills. This is not to suggest that energy subsidies should be moved from production to consumption side, but rather that the subsidies which are allocated to the former should be linked to the final consumption of the energy being produced. This would encourage wind power, and other electricity producers, to support and help develop effective and sustainable means for the consumption of that electricity which is being produced.

It is important to note that although increased electricity consumption would increase an individual consumer's electricity costs, because this increased consumption comes at the expense of lowering fossil fuel use in other energy sectors, the consumer would likely end up paying less for their overall energy use. Furthermore, electric vehicles could consume electricity in a flexible manner, and by doing so aid in the integration of fluctuating renewable energy sources such as wind. This flexibility refers to the vehicle battery's capacity to both store electricity and deliver stored electricity back to the grid if necessary. Of course, this can only happen when the vehicle is plugged in. Therefore, drivers would have a responsibility to plug in their vehicles at appropriate times. The possibility of lower energy costs could encourage consumers to take on this new responsibility. It is possible, due to the relative inelasticity of energy demand, that relying on individual consumers to fulfil this function could prove ineffective. However, this could open up the potential for a professional aggregator market where the response of demand to price would be more pronounced.

The model which was created to perform the analysis relies on several assumptions. Some of the most important of these have to do with the behaviour of the electricity market, specifically how price is affected by supply and demand and how it will fluctuate in the future. A correlation has been found between price and demand, which mainly can be explained by the general reduction in electricity price during night hours due to generally lower consumption during this time. To be sure, the price of electricity is not set by consumers and during the investigated period (2002 – 2013) demand for electricity has remained constant, even in times of economic crisis, as was the case in 2008. However, despite consumers being price takers at any point in time, the prices they "take" are, due to the merit order effect, lower when demand is low and higher when it is high. This effect is further accelerated concurrent with the increase in wind power share of total consumption. Future analysis could benefit from more thoroughly investigating how fluctuating renewable electricity production affects the relationship between demand and price.

The proposed strategy addresses socio-economic issues which hinder the deployment of electric vehicles on the local community scale. These issues will surely grow in complexity as the strategy is scaled up. Nevertheless, local communities provide effective testing grounds for the introduction of an integrated electricity and transportation sector. It could very well be that implementing the integration strategy on a local level could help to identify any issues that may occur on a national level. Solutions to these issues could then be developed prior to a national rollout. It may even be the case that the national implementation is built up from a network of local communities. The option of electrifying heat production units may also provide a means of increasing flexible electricity consumption and consequently help to reduce the PSO. Future studies might look more closely into the heating sector in this regard. In any case, the Danish national plans do advocate a move away from fossil fuels in all energy sectors. Therefore, some method of electrifying the transport sector would have to eventually be applied. While the strategy proposed here might not work as a stand-alone solution in the national context, it may very well prove to be an integral part of a complete policy and technology package which the Danish Government can use to achieve its goals.

Based on the findings presented here, it is recommended that the Danish Government reconsider their subsidy and tax allocation policies in order to provide funds for projects which seek to integrate energy sectors. This may require wind project developers who are applying for tender to be evaluated under a more stringent set of criteria. This could mean looking at both the supply and demand side benefits of proposed projects and specifically how they might help to increase flexibility in the latter. Accordingly, a wind energy producer might have to outline in their application for tender how they plan to integrate with other sectors of the energy system and possibly how they plan to distribute subsidised funds to supply and demand side aspects of the wind project. Integrating energy sectors would likely require significant participation from individual energy consumers as well. Indeed, establishing a smart energy system would require that the production units and associated infrastructure (CHP, electric transport, heat pumps, wind turbines, etc.) be implemented on a local level. As community owned wind projects are more likely to engage individuals than privately owned endeavours, it is further recommended that the Danish Government focus on the former when allocating subsidies. In this regard the government might do well to stipulate that the amount of community involvement in a project, both in terms of ownership and in terms of the commitment of individuals to purchase electricity consuming units such as electric vehicles, must be a contributing factor in deciding how much funding will be allotted to a project.

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