The electricity market in a renewable energy system

Djørup, Søren Roth; Thellufsen, Jakob Zinck; Sorknæs, Peter

Published in:
Energy

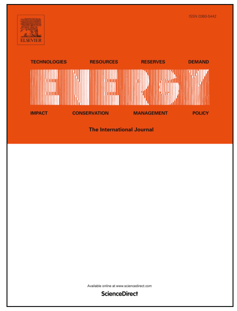
DOI (link to publication from Publisher):
10.1016/j.energy.2018.07.100

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Djørup, S. R., Thellufsen, J. Z., & Sorknæs, P. (2018). The electricity market in a renewable energy system. *Energy*, *162*, 148-157. https://doi.org/10.1016/j.energy.2018.07.100

Accepted Manuscript



The electricity market in a renewable energy system

Søren Djørup, Jakob Zinck Thellufsen, Peter Sorknæs

PII: S0360-5442(18)31397-5

DOI: 10.1016/j.energy.2018.07.100

Reference: EGY 13365

To appear in: *Energy*

Received Date: 31 October 2017

Revised Date: 9 July 2018

Accepted Date: 15 July 2018

Please cite this article as: Djørup Sø, Thellufsen JZ, Sorknæs P, The electricity market in a renewable energy system, *Energy* (2018), doi: 10.1016/j.energy.2018.07.100.

The Electricity Market in a Renewable Energy System

Søren Djørup[a1], Jakob Zinck Thellufsen[b], Peter Sorknæs[c]

[a]Department of Planning, Aalborg University, Rendsburggade 14, DK-9000 Aalborg, Denmark; djoerup@plan.aau.dk

[b]Department of Planning, Aalborg University, Rendsburggade 14, DK-9000 Aalborg, Denmark; jakobzt@plan.aau.dk

[c]Department of Planning, Aalborg University, Rendsburggade 14, DK-9000 Aalborg, Denmark; sorknaes@plan.aau.dk

Abstract

The transition to a 100% renewable energy system based on variable renewable energy raises technical but also institutional questions. The smart energy system concept integrates variable renewable energy by addressing the technical challenges through the integration of different energy sectors, but integration of variable renewable energy also entails a change in the cost structures, especially related to electricity. The effect of this change in cost structures on market prices is investigated. This is done through simulation of a 100% renewable energy system that utilises a large degree of cross-sector integration but maintaining the current electricity market structure. The paper uses a 100% renewable energy system scenario for a 2050 Danish energy system. This is reflected in the use of wind energy as the primary renewable energy source. It is concluded that the current electricity market structure is not able to financially sustain the amounts of wind power necessary for the transition to a 100% renewable energy system. Since earlier research shows that neither electricity production costs nor the total system costs is higher for the renewable path than the fossil-based alternatives, the conclusion in this paper points towards a need for reshaping the institutional structure of electricity trade.

Keywords: Smart energy systems, electricity market, wind power, renewable energy

Abbreviations

SES: Smart Energy System

CHP: Combined heat and power

CHP2: Decentralised combined heat and power plants

[1] Corresponding Author; Tel: +45 93562365

CHP3: Centralised combined heat and power plants

PP: Power plants

VRES: Variable Renewable Energy Sources

DK1: Western Denmark

1 Introduction

The radical change of traditional fossil fuel-based energy systems to systems based on variable renewable energy sources involves both technical and institutional challenges. In the transition towards 100% renewable energy systems, one suggested pathway is the smart energy system (SES) [1–4]. Smart energy systems rely on three main components: smart electricity grids, smart thermal grids, and smart gas grids [5]. These main components are all interconnected to achieve the most efficient solutions to the integration of variable renewable energy sources (VRES).

Smart energy systems are founded on the idea of basing future energy systems on VRES [5]. This means that production of energy from wind turbines, photovoltaics, solar thermal, etc., is the main source of energy in the system [6]. This creates a large amount of VRES [7], especially in the form of electricity that has to be utilised in the energy system to supply demands that to a large extent might not timely align with the variable production. Smart energy systems utilise system integration [4,8], where the different energy sectors are interconnected in order to create flexibility between the energy supply and the energy demand in 100% renewable energy systems and to deliver energy as efficient as possible in the right time, quantity and quality [9].

To create these integrated energy systems, smart energy systems rely on several technologies to increase the utilisation of variable renewable energy systems. Smart energy systems utilise heat pumps to convert electricity to heat, both in individual heating and district heating. This allows for the use of efficient thermal storages that are more cost efficient than electricity storages [1,10]. It utilises power-to-gas technologies to convert electricity from wind and solar to synthetic gases and electrofuels [11,12] that can be used in power plants, combined heat and power plants, and the transportation sector [12]. These fuels are also easily stored in already available storage facilities, like oil tanks and gas grids [1].

The technical aspects of the SES are investigated in several papers. These can primarily be divided into two groups. The first group focuses on designing entire integrated energy systems. For example, for the European Union [12,13], countries such as Denmark [14,15], Ireland [16], Portugal [17], as well as cities and municipalities such as Copenhagen [18,19], Aalborg [20], and Sønderborg [18]. The second group of papers investigates specific aspects of the smart energy system. Examples are the benefit of flexible energy demand [2], the implementation of heat pumps [21], how Smart energy systems work in relation to electricity interconnection with other countries [22], the interplay between energy savings and integrated energy systems [23,24], utilising vehicle-to-grid technology [25], and the role of different type of energy storages [1,10].

Common for these studies is that they investigate the technical operation of the energy system. Together they create a framework where the goal is to lower the fuel consumption. This article takes point of departure in the technical scenarios developed within the SES framework. Studies have shown the technical and economic feasibility of such systems [15,26]. The central economic question regarding SES, thus, has an institutional and organisational character [9,27–30]. A pertinent question is: to what extent current market structures can support the massive increase in variable renewable energy capacities that are the main pillars of future SES?

From an economic perspective, the replacement of fuels with wind and solar energy is a substitution of short-term fuel costs with long-term capital costs. The radical change in the technical aspects of the system, therefore, leads to questions about how the market and governance structures should be shaped [9]. A pertinent issue is the match between the current electricity spot market design and the introduction of fuel-free technologies, such as wind turbines and photovoltaics. The low marginal production costs of these fuel-free technologies affect the market prices in a downward direction. In the literature this is referred to as the merit order effect [28,31–34].

In this article, we briefly outline a theoretical basis of the merit order effect and recent empirical indications of this theoretical effect. Afterwards, our purpose is to investigate to what extent the mismatch between technologies and institutions is so severe that the current electricity market structure becomes a barrier for realising the visions of a 100% renewable energy supply. The starting point for this analysis is the SES approach. Thus, in order to create a more efficient energy system with high utilisation of variable renewable energy, the analysed energy system contains implementation of heat pumps—both in individual heating and in district heating—smart charge technology and vehicle-to-grid in combination with other flexible electricity demand, and power-to-gas technologies.

To illustrate the potential issues, the study deals with the example of a 100% renewable energy system for Denmark. Studies [35–37] point to a high demand for wind power in a future Danish energy system. Thus, this study specifically investigates the potential gross revenue from a marginal price market with a high penetration of wind power.

2 Current market structures: The merit order effect in theory and practice

In the research regarding electricity wholesale markets, it is standard economic theory to assume the supply curve and the resulting market prices, which are derived from the marginal cost of supply in an auction-based system [38]. This textbook assumption is based on the premises of the so-called full competition. We understand the requirement of full competition as a market condition, where the individual supplier is disciplined by the competition from other suppliers to not bid into the market with a price above the marginal supply costs.

What constitutes the marginal supply costs is not specified in standard economic textbooks. Which marginal cost that matters for the price formation is a result of the concrete institutional setting. Thus, the expected marginal cost formation must rely on an analysis of the concrete rules and procedures that structure the trade in the specific market that is analysed.

In the Nordic countries, the Nord Pool Spot market is designed as an hourly auction. In principle, it will be the hourly supply cost, which becomes the marginal costs. These shape the market prices.

Having no fuel consumption, wind power, and photovoltaics have no marginal costs within such a market structure. The effect of this is well known in the literature and is usually referred to as the merit order effect [28,31–34, 39].

Combining the textbook theory from economics with the knowledge of trade procedures at the Nord Pool Spot, the expectation that the introduction of wind power and photovoltaics into the electricity system should have a downward pressure on market prices.

The existence of the merit order effect is observed in several publications. It is well described how the introduction of wind, photovoltaics, and other alike technologies will lead to declining market prices when introduced in the current market structures [28, 31–34, 39].

An empirical supplement to the existing literature is presented below. Figs. 1–3 presents some calculations carried out on basis of hourly spot market data. The data behind the calculations is achieved from a database with electricity production and market data hosted by the Danish TSO, Energinet.dk [55).

Fig. 1 shows the development in average spot market prices in the Western Denmark (DK1) price zone in Nord Pool Spot. The general trend is declining prices, and it can also be observed that the prices for wind production is, on average, lower than the average for the total yearly production. Fig. 2 shows the correlation between wind power and market prices. As depicted, the trend is that increased wind power production results in a stronger correlation between wind power production and market prices. The correlation, of course, is negative; therefore, hours of high wind production results in lower prices. Fig. 3 shows that the increase in wind power production is more-or-less mirrored in a decrease in central power plant production—as would be expected from the market theory.

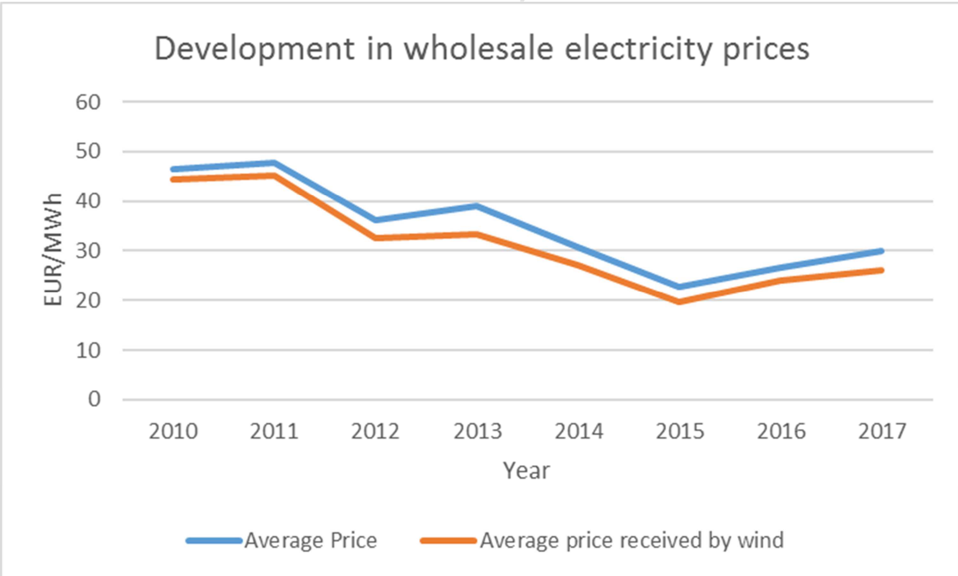


Fig. 1. The development in spot market prices in Western Denmark (DK1).

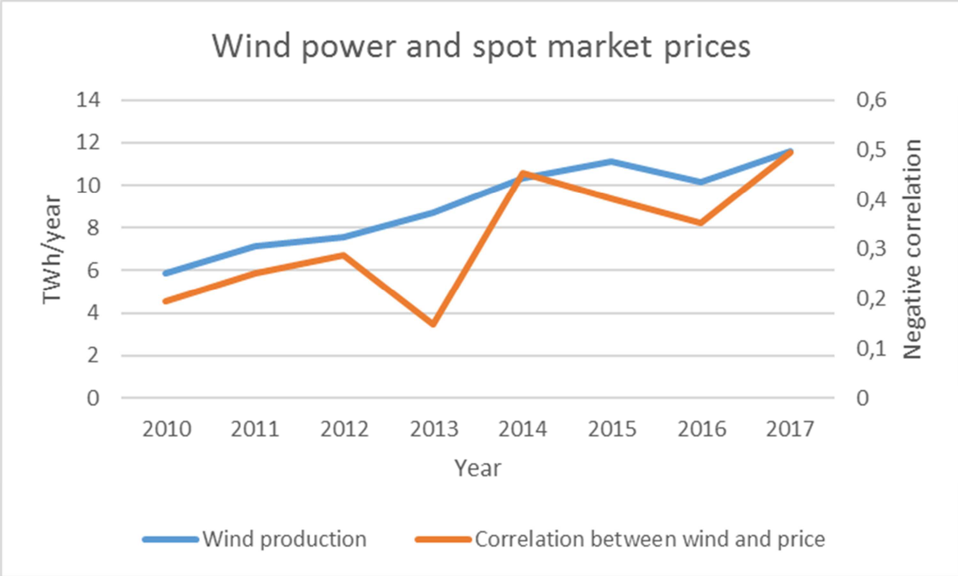


Fig. 2. Development in wind power production and the correlation between wind production and market prices in Western Denmark (DK1).

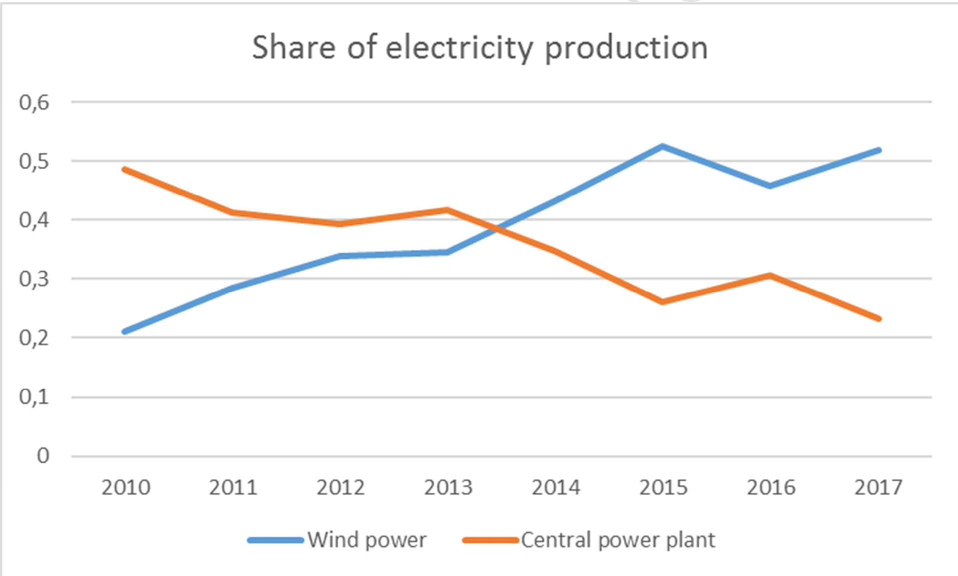


Fig. 3. The share of electricity production in Western Denmark (DK1) from wind power and central power plants.

In a broader system perspective, the declining market prices can be understood as a natural consequence of the condition that the primary energy production is undergoing a substitution of fuels with physical capital, such as wind turbines.

As a consequence of this technical substitution, this study argues that smart energy systems require different electricity markets than the traditional fuel-based systems. Currently, electricity markets are in most cases based on a short-term marginal cost approach. This makes sense in a fuel-based energy systems where the supply costs are more closely linked to the short-term marginal costs (e.g., fuel costs), and there is a mix of different units with different short-term marginal cost. Since short-term costs are higher in a fuel-based system, it is relevant with a market that is designed to minimise these costs. As costs become more connected to long-term capital costs, and less related to short-term fuel costs, institutional structures addressing the short-term costs become less influential to the total system costs.

The actual price development within the current market design, now and in the future, is shaped by many other factors than the development in marginal supply cost. However, it is the view in this paper that there will be a long-term downward pressure on electricity wholesale market prices if current market structures are kept in place during the technological transition. Referring to the merit order effect, the economic properties of the supply side forces must be manifested in the prices as the transition proceeds. In systems where the bulk part of primary energy supply is stemming from wind turbines, the sustainability of electricity market structures becomes vital for the system as these should financially sustain investments in wind turbines.

The critical question is, therefore, whether the implications of the described economic properties are so significant that it will prevent the transition from succeeding, as the market conditions might make needed investments in wind power unfeasible for investors. To address this question, we carry out a market analysis in a simulated SES, assuming the current electricity market structures remains unchanged.

Specifically, we use a designed SES for Denmark with 100% renewable energy, assuming electricity markets structure equivalent to the current Nord Pool Spot market. The method behind the analysis is described in the next section.

3 Methods

Several steps are needed to investigate whether a payment corresponding to the price derived from hourly marginal production cost is sufficient to cover the investments of renewable energy in a SES. Due to the electricity market structure that wants to be investigated, the study needs to analyse the hourly operation of a 100% renewable SES. In each hour, the marginal electricity producing unit must be identified, as well as the production on all the units in the energy system. Based on fuel prices and other variable operation costs, the marginal cost for each unit in each hour must be identified as well. By having these three outputs, it is possible to identify the theoretical market price in every hour and, thus, identify the specific hourly payment to the variable renewable energy sources.

By taking the simulated production profile into account, the study then summarises these hourly revenues into total yearly earnings. Knowing the yearly income from the produced energy, the private return on capital can be estimated on basis of assumed investment costs.

To identify the hourly operation of a SES, the study uses EnergyPLAN as the energy system simulation tool. The ‘IDA’s Energy Vision 2050’ scenario for a 100% renewable energy system of Denmark in 2050 is used as the scenario simulated in EnergyPLAN [15]. ‘IDA’s Energy Vision 2050’ explores a pathway towards transitioning the Danish energy system to 100% renewable energy. It compares the path to similar studies for Denmark, to create an efficient scenario with less sensitivity to the development of energy prices in the future. This results in a scenario for a future Danish energy system. In that sense, the scenario takes advantage of system integration technologies to reach an efficient utilisation of variable renewable energy. Therefore, the ‘IDA’s Energy Vision 2050’ scenario illustrates the principles of a fully integrated SES in 2050 based on large amounts of variable renewable energy.

EnergyPLAN is an advanced energy system tool, developed at Aalborg University [40]. EnergyPLAN simulates the operation of an entire energy system, including electricity, heating, industry, and transport, on an hourly basis [41]. Either these simulations can be based on the objective of reducing fuel consumption (i.e., technical simulation) or on the objective of reducing short term marginal costs (i.e., market simulation). EnergyPLAN runs deterministic simulations based on analytical programming; therefore, with the same inputs, the same outputs are achieved. Fig. 4 illustrates the links between the different energy sectors in EnergyPLAN.

The links shown in Fig. 4 are tied to the smart energy systems concept. It shows that each energy sector is modelled and that EnergyPLAN creates links between them. EnergyPLAN models the electricity system by including the classical electricity demand, such as for appliances and lightning, but also electricity demand derived from heating and transport systems running on electricity. The user defines the size of the potential units for producing the needed electricity. This includes renewable energy sources as wind and solar, but also power plants of different types, combined heat and power plants, hydropower, and electricity storage. EnergyPLAN can prioritise between these units, depending on either a marginal cost perspective or a fuel efficiency perspective. The black lines in Fig. 3 show the structure and flows of the electricity system as well as how it plays together with industry, transport, and heating demands.

EnergyPLAN models the heating sector as two different types of demands: either an individual heated building or buildings connected to district heating. The individual heated building, in this case, operates on heat pumps and biomass boilers and, therefore, results in either an increased electricity demand or an increased fuel demand. The district heating system interoperates with the electricity system and transport system. The system includes combined heat and power plants, which produce both electricity and heat. The district heating system also includes thermal storages, on which heat from the combined heat and power (CHP) plant can be stored. Furthermore, the storage can store heat produced on a heat pump, generating flexibility excess electricity from wind turbines and the heat demand. The transport sector in EnergyPLAN utilises electrolysers and electrofuels to supply the heavy transport. From these processes, waste heat can be produced to the district heating grid. Thus, there is a link between excess electricity production and hydrogen production, heat production, the gas system, the heat system and the electricity system. Finally, the industry sector can also deliver waste heat to district heating. The interoperability and flows can be identified on the orange line in Fig. 3.

The transport demand primarily gives an option of using electricity and electrofuels as energy carriers. However, this interconnects the transport system directly to the electricity system, and indirectly to the district heating system.

The final energy system utilised in EnergyPLAN is the fuel system. The yellow line in Fig. 3 highlights the fuel system. In a traditional energy system, the system is primarily reliant on imported fuels, like oil, gas, and coal. However, EnergyPLAN allows for production of fuel from excess electricity or other biomass resources. While biogas and biofuels are produced separately, the production of electrofuels enables the use of excess electricity; whereas, the plants also produce waste heat for district heating. These fuels are used for transport, but also for energy generation in boilers and power plants. Thus, the production of fuels creates a loop, where excess electricity in hour can be stored as a fuel, used in a heavy duty truck in another hour, or utilised in a power plant in hours with low availability on the VRES.

This large degree of interoperability between all the main energy sectors makes EnergyPLAN useful for analysing the impact of renewable energy in an integrated energy system. The interoperability makes it possible to utilise the VRES in multiple sectors, such as heat pumps for heating, electric vehicles with smart charge and vehicle to grid, hydrogen production, and storages. Together, this should create a higher utilisation rate and demand for electricity, thus, creating more situations with potential for income for VRES. Thus, the EnergyPLAN model creates a better framework for analysing the impacts of large shares of VRES, such as wind, compared to a tool that only can model the electricity sector for instance. EnergyPLAN takes into account the potential ways of using VRES in a SES.

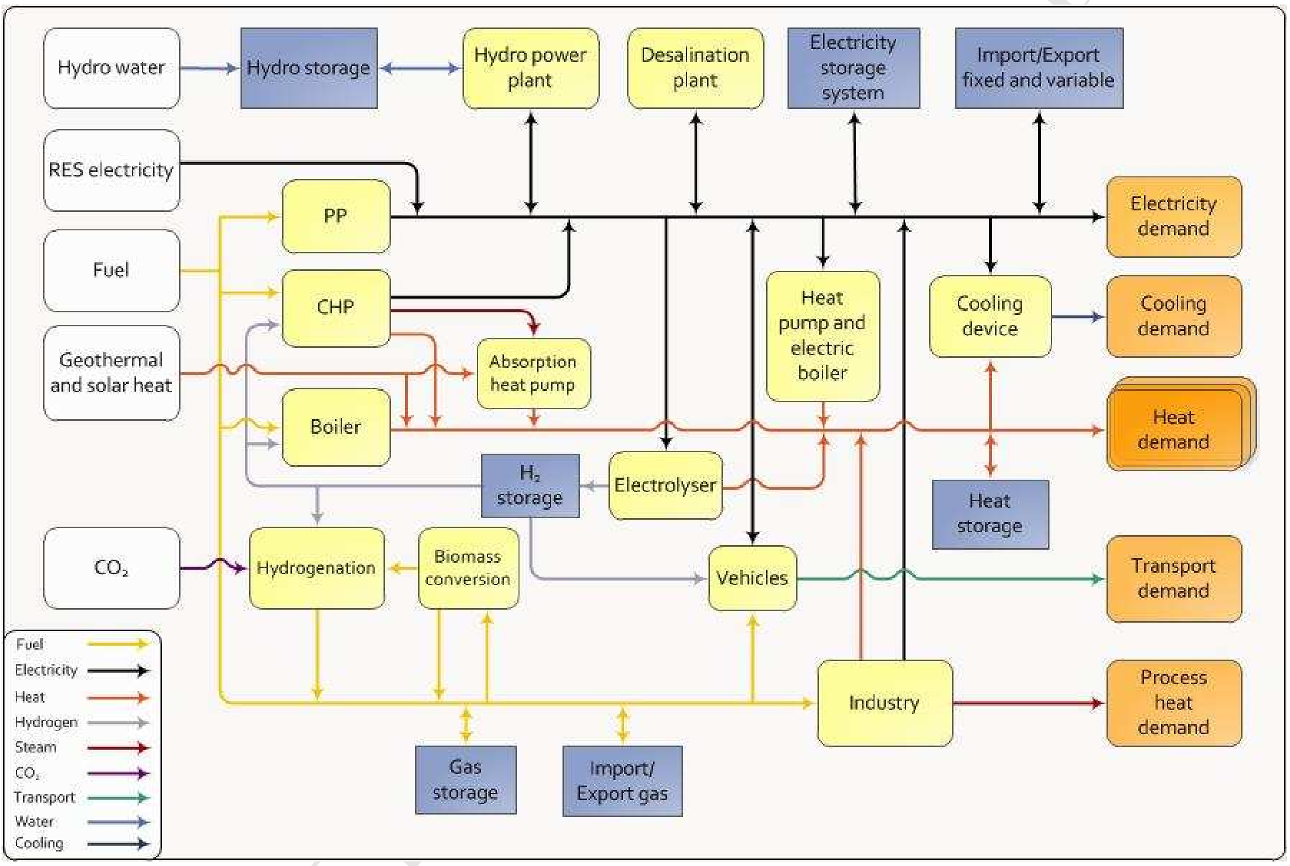


Fig. 4. Overview of EnergyPLAN's approach to smart energy systems showing the sectors being analysed and their links [39].

EnergyPLAN has been used for many aspects of energy systems analysis and based on the large amount of potential measure points, it is possible for the user to discuss possible solutions for an energy system [42]. For instance, it has been used for modelling future energy scenarios for countries [17,35,43–46], regions, and cities [18,19,47–49]; it has been used for the investigation of the implementation of certain technologies [10,23–25,50,51]; and it has been used to investigate pathways for different renewable energy sources [44,52].

The first step of the analysis is to simulate the operation of the scenario from 'IDA's Energy Vision 2050'. The 2050 scenario is used, which is simulated based on the technical simulation strategy, achieving a fuel-efficient operation of the entire energy system. The scenario is based on a range of different potential future fuel costs. The scenarios are run exactly as they are described in 'IDA's Energy Vision 2050', meaning they rely 100% on renewable energy and an integrated energy system utilising heat storages, gas storages, heat pumps, and power-to-gas. Also, flexible electricity demands and electric vehicles with smart charge technology are implemented. Since the primary source of energy is wind power, this is the main emphasis of the analysis. Table 1 shows installed capacity of VRES. For comparison, the annual electricity consumption is 94.11 TWh in the 2050 scenario. This also shows why this study emphasises onshore wind power and offshore wind power, as these are the main producers of energy, not only in the electricity sector but in the entire energy system.

Table 1
Assumptions for variable renewable electricity capacity and production in the IDA's Energy Vision 2050 scenario [15].

	Installed capacity [MW]	**Yearly production [TWh]**	**Share of annual electricity consumption**
Onshore wind	5 000	16.20	17%
Offshore wind	14 000	63.76	68%
Photo voltaic	5 000	6.35	7%
Wave power	300	0.05	0%

The focus on wind power is due to the analysed energy system of Denmark. However, the study should be seen as principal in terms of the SES, which could potentially be of any size, and the main energy source could be solar power in a different system. As discussed earlier in this paper, solar power also has low short-term marginal costs and, therefore, also reduces the electricity wholesale market price in hours of production.

Based on a simulation of the SES, it is possible to identify the production of each unit in every hour. Thus, the marginal electricity producer in every hour is found. In principle, in terms of electricity, the following order is used to determine the marginal electricity producer in each hour:

1) VRES are the only producers of electricity. VRES are the marginal electricity production unit.
2) Centralised combined heat and power plants (CHP3) are producing electricity, but not decentralised combined heat and power plants (CHP2). CHP3 are the marginal producers.
3) CHP2 are producing electricity alongside CHP3. CHP2 are the marginal producing unit.
4) Condensing power plants are producing electricity. Condensing power plants are the marginal producing unit.

This order is determined based on the operation of the future energy system as fuel efficient as possible. Thus, the first units set to operate are the technologies that do not use any fuel. Then, the combined heat and power plants sets the price since they are more fuel-efficient than running a power plant and a boiler. In this specific example, the CHP3 are more efficient than the CHP2. Finally, the least efficient way of producing electricity in this scenario is the operation of condensing power plants. In the specific example here, this order also corresponds to the order of the marginal prices on the different units. Table 4 shows that the merit order above is equal to the order of the marginal prices.

The simulation applied in EnergyPLAN is based on a technical priority order that is identical to the one outlined above, and it aims to reduce fuel consumption. However, the outlined order corresponds to the hourly marginal cost merit order, which is why the fuel minimising simulation strategy in this instance is applicable as a market analysis.

By comparing the outlined order of determining the marginal producing unit with the simulated hourly production profiles over the year, it is possible to determine which supply unit sets the price in every hour. The actual marginal production cost in every hour, M_{cost} (see Equation 1), that each unit has, is dependent on fuel costs (F_{cost}) and variable operation and maintenance costs ($VO\&M_{cost}$), as the short-term electricity demand is assumed inelastic to price. Flexible demand in this study serves the purpose of limiting fuel consumption. In this study, the fuel costs and operation and maintenance costs are fixed for the whole year.

$$M_{cost} = F_{cost} + VO\&M_{cost} \tag{1}$$

Future fuel prices are by nature uncertain, so this study operates with three scenarios of fuel prices: low, medium and high. Table 3 shows the assumption for fuel prices. These are based on the three scenarios in “IDA’s Energy Vision 2050” [53], Table 2 shows the variable operation and maintenance costs which are held fixed while fuel costs are varied. These are based on the Danish Energy Agency’s cost database [54]. The resulting marginal production costs for each of the units are highlighted in Table 4.

Table 2

Variable operation and maintenance costs [53].

Category	**Technology**	**VO&M Cost [EUR/MWh]**
District heating and CHP Systems	Boiler	0.15
	Combined heat and power	2.70
	Heat pump	0.27
	Electric heating	0.50
Power plants	Hydro power	1.19
	Condensing power plant	2.65
	Geothermal	15.00
	Gas to liquid Module 1	1.80
	Gas to liquid Module 2	1.01
Storage	Electrolyser	0.00
	Pump (charging unit)	1.19
	Turbine (discharging unit)	1.19
	Vehicle to grid discharge	0.00
	Hydro power pump	1.19

Table 3

Fuel costs in the different price scenarios [53].

[EUR/GJ]	**Coal**	**Fuel Oil**	**Diesel**	**Petrol**	**Gas**	**Biomass**	**Dry Biomass**
Low	2.7	8.8	11.7	12.7	5.9	5.6	4.7

Medium	2.8	11.6	16.0	16.4	8.3	6.0	10.9
High	3.4	16.1	19.6	20.6	10.4	8.1	6.3

Table 4

Resulting marginal costs depending on fuel costs and the marginal production units [53,54].

	Low fuel costs	**Medium fuel costs**	**High fuel costs**
Variable renewable energy sources (VRES)	0 EUR/MWh	0 EUR/MWh	0 EUR/MWh
Running power plant	52 EUR/MWh	66 EUR/MWh	79 EUR/MWh
Running central CHP	44 EUR/MWh	59 EUR/MWh	68 EUR/MWh
Running decentral CHP	49 EUR/MWh	64 EUR/MWh	73 EUR/MWh

By combining the knowledge of exactly how the 100% renewable energy system operates in each hour of the year, what the marginal producing unit is in every hour, and what the cost is of operating that unit, it is possible to find the electricity market price and the resulting annual income for wind turbines. These earnings are compared with the investment costs for the onshore and offshore wind turbines, respectively. Here, the study uses two different assumptions for investment costs and fixed operation and maintenance costs. The first scenario is based on current 2015 prices, while the second scenario is based on assumed 2050 prices. Both price scenarios are from the Danish Energy Agency [54]. Table 5 shows the cost scenarios for onshore and offshore wind turbines.

Table 5

Cost data on onshore and offshore wind turbines for 2015 and 2050 price scenarios [54].

	2015 price scenario	**2050 price scenario**
Total onshore wind investment [M€/MW]	1.07	0.83
Annual onshore wind O&M [M EUR]	173	140
Onshore wind technical lifetime [years]	25	30
Total offshore wind investment [M€/MW]	2.46	1.39
Annual offshore wind O&M [M EUR]	1,076	590
Offshore wind technical lifetime [years]	25	30

With the above information, it is possible to calculate the private profitability of wind power. It is important to highlight that this economic return cannot be conceived as the socioeconomic feasibility of wind power, but it should be understood as the return on capital a private investor can obtain within the current electricity market structure, excluding feed-in tariffs and other possible non-market payments but assuming a 100% renewable smart energy system. The system is only simulated for one year, and the study assumes the same income every year throughout the wind turbines' lifetime. Thus, the estimated yearly income may be interpreted as a yearly average income.

4 Results

What becomes apparent from simulating the system is that approximately 55% of the hours have wind or solar power as the marginal producer. This means that in over half the hours of a year the only production of electricity comes from VRES. In those hours, the electricity market price is zero; thus, there will only be an income for the wind turbine owner in 45% of the hours during the year. Power plants determine the marginal price in 36% of the hours during the year, while CHP plants determine the marginal price in 9% of the hours of the year. The specific hours can be seen in Table 6. Please note that EnergyPLAN simulates leap years.

Table 6

Number of hours where different technologies set the marginal price.

Marginal producer	**Hours**	**Share of annual hours**
Variable renewable energy sources (VRES)	4850	55%
Centralised combined heat and power plants	1	0%
Decentralised combined heat and power plants	808	9%
Power plants	3125	36%

The financial challenge for wind energy investments becomes clearer when looking at the energy amounts produced from various technologies. In the simulation, most of the yearly wind production occurs in hours where VRES are the marginal producer. Fig. 5 illustrates this by comparing the energy production from the different units in every hour with the marginal producer. Fig. 5 also shows that for onshore wind turbines, 81% of its energy production is sold at zero prices; in other words, hours where a variable renewable energy technology is the marginal producer, 74% of the offshore wind production hours occur at a zero price. Onshore wind turbines, therefore, only receive an income on 19% of their supplied energy to the system. For offshore wind turbines the income situation is slightly better, with 26% of their energy traded in hours where a fuel-fired plant is the marginal supplier.

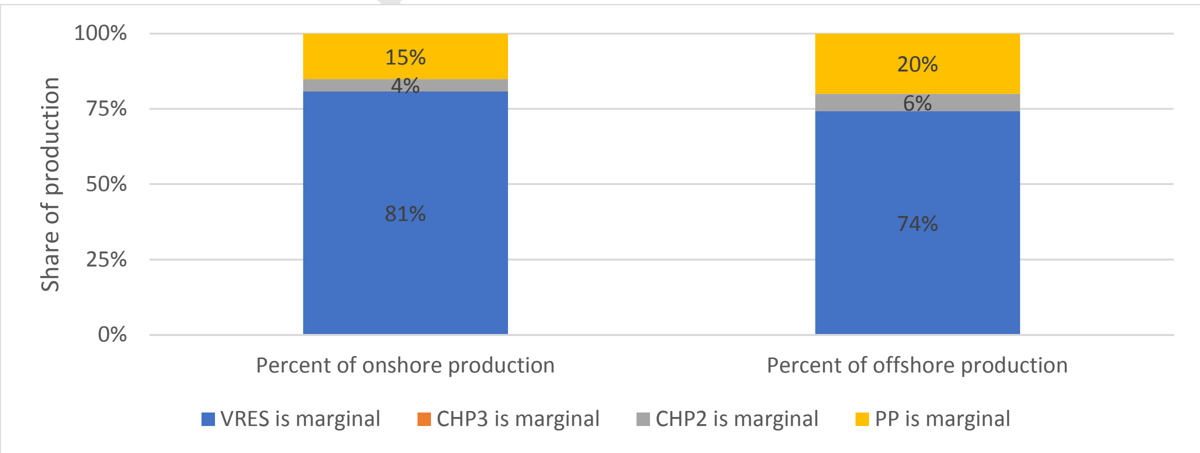


Fig. 5. The share of production on wind turbines that occurs when different technologies are marginal producers. VRES include both wind and solar, CHP3 is centralized combined heat and power plants, CHP2 is decentralized combined heat and power plants, and PP is condensing power plants.

To illustrate how this income is distributed through the year, Fig. 6 shows a duration curve of the hourly income on onshore and offshore wind, using the medium fuel prices. This shows that 50% of the income comes from producing only around 1,000 hours a year, both for onshore and offshore wind.

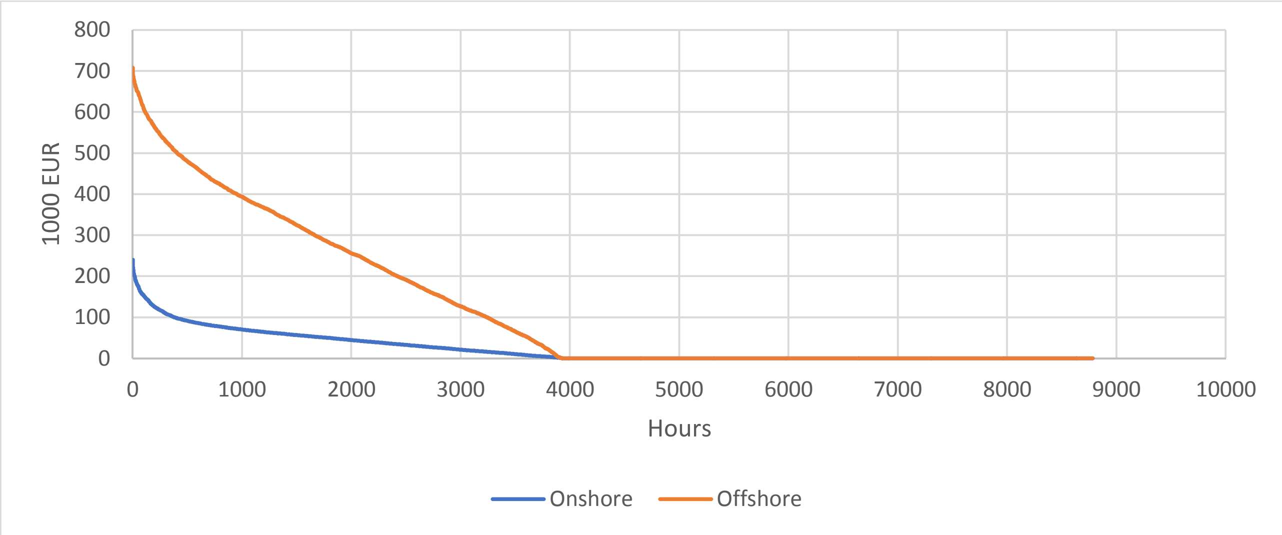


Fig. 6. Duration curve of the income on the installed onshore and offshore wind turbines in a medium fuel price scenario.

It is apparent from the figures that current electricity market structures may only be a limited source of income for wind power in the future. It should be underlined that these results are the output of a system where there is a high implementation of technologies for integrating wind energy in the heat and gas sector. The results indicate that these technologies—despite their large and well-documented technical and socioeconomic benefits—may not suffice as long term means for sustaining the current electricity market structure. Even though the demand side is boosted in hours of high wind, the supply side force of the large amounts of wind energy in the system will dominate the price formation. As long as zero marginal cost technologies are the marginal supplier in a competitive environment, this study indicates that demand side initiatives do not raise price levels significantly within an hourly auction design.

To conclude whether the income from the electricity market is enough, the income level has to be compared with the investment costs. To do this, the study calculates the internal rate of return as an expression of private profitability. Table 6 and Table 7 show the internal rate of return for all scenarios, based on the assumption that each year generates the same income and that this income can be generated for all the wind turbines' lifetime. The "N/A" results indicate scenarios where the annual earnings are lower than the annual costs, meaning annual cash flows throughout the lifetime is negative. The results, here, show that the internal rate of return is negative in most scenarios, meaning the yearly income is not large enough to give a positive return on capital. In one scenario, the estimated internal rate of return is zero, which is not enough to attract private capital for the investment. In general, this simply means that there are too small revenues in the market to sustain investments in VRES. Therefore, the current market structure is unable to financially sustain wind energy in a smart energy system.

This points to the conclusion that complementary institutions, such as feed-in tariffs, or a more fundamental restructuring of the electricity market design is necessary for providing sufficient VRES in a 100% renewable energy system.

Table 6

Internal rate of return for onshore wind.

	Low fuel costs	Medium fuel costs	High fuel costs
2015 prices	N/A	-12%	-7%
2050 prices	-10%	-4%	-2%

Table 7

Internal rate of return for offshore wind.

	Low fuel costs	Medium fuel costs	High fuel costs
2015 prices	N/A	N/A	-11%
2050 prices	-5%	-2%	0%

4.1 Discussion of key methodological choices

Some methodological choices are important to discuss, as these choices potentially influence the estimated price levels and the private profitability of wind power investments.

First, the simulation is run as a closed market model, meaning that no exogenous market has been linked up to the simulated energy system. Naturally, if a system dominated by variable electricity sources is surrounded by high price fuel-based systems, connecting to these areas may be a strategy to sustain the market revenues for wind power and alike technologies. However, there are both methodological as well as analytical reasons for why the system has been simulated as a closed system.

In the long run, it is assumed that all countries strive towards fossil fuel free systems. In this perspective, it is not a viable strategy to analyse smart energy systems as small renewable islands surrounded by neighbouring high price fuel-based systems. The very premise for this paper is to investigate the economic properties of a system where wind power and photovoltaics are the dominant sources of energy.

In addition, because the external markets would be modelled as exogenous parameters—including those in the analysis—they may cover up financial imbalances in the system as the one uncovered above. Because the external market prices are not derived from a specified system, but is only included as an assumed price distribution, they enter the analysis as a sort of 'random' factor that might potentially have a large influence on the model outcome. Such element, therefore, potentially blurs the intrinsic economic dynamics of the SES, which is the subject of this paper.

It should also be added that the present analysis is done based on a technical scenario for Denmark with no significant internal bottlenecks. For the present purpose, the geographical location and extent of the scenario is not the main issue. The analysis is based on the chosen scenario due to the character of its technical design: a full scale SES. In principle, a SES for Europe could be simulated as a closed system, thus, implying no limitations in electricity flow between nations.

Second, there is an assumption of full competition on the supply side. This means that it is assumed that prices strictly reflect marginal production costs. Weakened competition among suppliers may clearly allow marginal producers to charge above marginal costs and, thereby, raise price levels. However, since market structures, such as the Nord Pool Spot market, is designed with the assumption of full competition, it is appropriate to evaluate these markets structures with the assumption of full competition. In other words, we assume the markets to work as they are designed to work.

5 Conclusions

The introduction of VRES, such as wind power and photovoltaics, poses both technical and organisational challenges to the energy system.

The technical challenges of VRES have been addressed in literature under the concept smart energy systems. An organisational challenge is derived from the parallel shift from short-term to long-term costs associated with the substitution of fuels with physical capital.

It is well documented that this change in the technical production basis results in a downward pressure on electricity spot-market prices with the current electricity market paradigms in use. In this paper, we have addressed whether this economic effect is so severe that it will undermine the financial sustainability of the technical and economic efficient solutions proposed in the smart energy systems literature. By calculating theoretical market prices in a 100% renewable energy system, we find the force of the merit order effect to be a barrier for realizing a 100% renewable energy system based on variable renewable electricity sources. It is shown that the estimated return on capital for private wind energy investors is non-existent and might even be negative. These results suggest that it is not probable that the current electricity market structures will be able to financially sustain VRES as the dominating primary sources of energy. As at least half of the primary energy supply is fed in through the electricity system, these identified shortcomings in its current financial structure may be perceived as a barrier for the provision of primary energy supply in a SES.

So far, the introduction of renewable energy has—to a large extent—been provided through feed-in tariffs and other comparable schemes. These schemes are often referred to as subsidies, implying that they are temporary necessities until renewable energy technologies mature. This study suggests that the long-term necessity of the schemes is not related to technological inefficiency but a permanent mismatch between cost structures and the current specific market structures.

Thus, as wind power (and photovoltaics) gradually matures, it may be a misinterpretation to regard the feed-in tariffs as temporary subsidies that are to be removed. While these policies may have originally been introduced to the system as subsidies for wind power at an early technological stage, they should now be understood as market supporting instruments that ensures the financial sustainability of the system in a long-term perspective.

However, this financial necessity of feed-in tariffs is due to the specific design in the Nord Pool Spot market that induces the hourly cost based low market prices. There is nothing faulty with the spot market construction in itself, as long as its limitations is understood and supplementing financial institutional elements (e.g., feed-in tariffs or comparable arrangements) are kept in place. Currently, the feed-in tariffs fulfil the gap between long term production costs and market prices derived from short term marginal costs. This gap seems to be a permanent condition – at least while the transition proceeds over the next 3-4 decades.

The calculations in this paper assume that market participants keep bidding based on (hourly) short term marginal costs. It could be discussed whether the bids in the very long term would stabilize at long term marginal costs. However, in the radical transition we are undergoing towards renewable energy systems, new capacity would constantly have to be introduced to the market. As long as this happens, we believe there will be a condition of competition on short term marginal costs.

For example, the political goal in Denmark is to have transitioned to a renewable energy system in 2050. This implies hard competition on short term marginal costs at least until 2050 - a condition that prevents the establishment of a long term marginal costs equilibrium. Meaning if a wind turbine is build today, it will be replaced two times before the long-term market equilibrium can possibly be established. Based on this, it is the conclusion that the current market design cannot be a financial engine for the transition to happen.

If the spot market is not redesigned while feed-in tariffs are removed, the results in this paper suggest that the electricity spot market design becomes a barrier to the transition to a 100% renewable energy system.

The solution to the market effects investigated in this article must be either: (1) keep market supplementing institutions, such as feed-in tariffs, in place or (2) redesign the market where wind energy is traded.

It is beyond the scope of this paper to investigate alternative market structures in any detail. Indeed, this important issue seems to call for its own paper. However, at least two basic requirements for an alternative market arrangement appears to us as important. First, since costs of wind power are long term in nature, contracts that finance this supply should be the same. Second, it is important that consumers of electricity bear the full cost of energy supply. While the first requirement is not met by present hourly spot market trading, current state-financed feed-in tariffs for wind power fails at the second requirement.

6 Acknowledgements

The work presented in this paper is a result of the research activities of the project "Innovative re-making of markets and business models in a renewable energy system based on wind power (I-REMB)" and the project "Renewable Energy Investment Strategies – A two-dimensional interconnectivity approach (RE-Invest)". The work has received funding from the Danish research program ForskEL and the Innovation Fund Denmark.

7 References

[1] Lund H, Østergaard PA, Connolly D, Skov IR, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016;11:3–14. https://doi.org/10.5278/ijsepm.2016.11.2.

[2] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems – A market operation based approach and understanding. Energy 2012;42:96–102. https://doi.org/10.1016/j.energy.2012.04.003.

[3] Lund H, Hvelplund F, Østergaard P, Möller B, Mathiesen BV, Connolly D, et al. Chapter 6 – Analysis: Smart Energy Systems and Infrastructures. Renew Energy Syst 2014; 131–84. https://doi.org/10.1016/B978-0-12-410423-5.00006-7.

[4] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.

[5] Lund H. Renewable energy systems: A smart energy systems approach to the choice and modeling of 100% renewable solutions. 2nd ed. Waltham (MA): Academic Press; 2014.

[6] Lund H. Large-scale integration of wind power into different energy systems. Energy 2005;30:2402–12. https://doi.org/10.1016/j.energy.2004.11.001.

[7] Becker S, Rodriguez RA, Andresen GB, Greiner MOW, Schramm S. What can transmission do for a fully renewable Europe? Proceedings of the 8th SDEWES Conference; Sep 2013; Dubrovnik; 2014.

[8] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. https://doi.org/10.1016/j.rser.2015.01.057.

[9] Hvelplund F, Djørup S. Multilevel policies for radical transition: Governance in a 100% renewable energy system. Environ Plan C Gov Policy 2017;35:1218–41. https://doi.org/10.1177/2399654417710024.

[10] Lund H, Salgi G. The role of compressed air energy storage (CAES) in future sustainable energy systems. Energy Convers Manag 2009;50:1172–9. https://doi.org/10.1016/j.enconman.2009.01.032.

[11] Ridjan I, Mathiesen BV, Connolly D. SOEC pathways for the production of synthetic fuels. 2013.

[12] Connolly D, Lund H, Mathiesen BV. Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. https://doi.org/10.1016/j.rser.2016.02.025.

[13] Connolly D, Lund H, Mathiesen BV., Werner S, Möller B, Persson U, et al. Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89. https://doi.org/10.1016/j.enpol.2013.10.035.

[14] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. https://doi.org/10.1016/j.apenergy.2015.01.075.

[15] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup SR, Nielsen S, et al. IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark. Aalborg, Denmark: Department of Development and Planning, Aalborg University; 2015.

[16] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100%

renewable energy system. Int J Sustain Energy Plan Manag 2014;1:7–28. https://doi.org/10.5278/ijsepm.2014.1.2.

[17] Østergaard PA, Soares I, Ferreira P. Energy efficiency and renewable energy systems in Portugal and Brazil. Int J Sustain Energy Plan Manag 2014;2:1–6. https://doi.org/10.5278/ijsepm.2014.2.1.

[18] Thellufsen JZ, Lund H. Roles of local and national energy systems in the integration of renewable energy. Appl Energy 2016;183:419–29. https://doi.org/10.1016/j.apenergy.2016.09.005.

[19] Mathiesen BV, Lund RS, Connolly D, Ridjan I, Nielsen S. Copenhagen Energy Vision 2050: A sustainable vision for bringing a capital to 100% renewable energy. Copenhagen, Denmark; 2015.

[20] Østergaard PA, Mathiesen BV, Möller B, Lund H. A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 2010;35:4892–901. https://doi.org/10.1016/j.energy.2010.08.041.

[21] Hedegaard K, Mathiesen BV, Lund H, Heiselberg P. Wind power integration using individual heat pumps – Analysis of different heat storage options. Energy 2012;47:284–93. https://doi.org/10.1016/j.energy.2012.09.030.

[22] Thellufsen JZ, Lund H. Cross-border versus cross-sector interconnectivity in renewable energy systems. Energy 2017;124:492–501. https://doi.org/10.1016/j.energy.2017.02.112.

[23] Lund H, Thellufsen JZ, Aggerholm S, Wittchen KB, Nielsen S, Mathiesen BV, et al. Heat saving strategies in sustainable Smart Energy Systems. Int J Sustain Energy Plan Manag 2015;4:3–16. https://doi.org/10.5278/ijsepm.2014.4.2.

[24] Thellufsen JZ, Lund H. Energy saving synergies in national energy systems. Energy Convers Manag 2015;103:259–65. https://doi.org/10.1016/j.enconman.2015.06.052.

[25] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy 2008;36:3578–87. https://doi.org/10.1016/j.enpol.2008.06.007.

[26] Hvelplund F, Mathiesen BV, Østergaard PA, Christensen P, Connolly D, et al. Lund H, editor. Coherent energy and environmental system analysis. Aalborg University: Department of Development and Planning; 2011.

[27] Djørup SR. Fjernvarme i Forandring: Omstillingen til vedvarende energi i økonomisk perspektiv [dissertation]. Aalborg University; 2016. https://doi.org/10.5278/vbn.phd.engsci.00137.

[28] Hvelplund F, Möller B, Sperling K. Local ownership, smart energy systems and better wind power economy. Energy Strateg Rev 2013;1:164–70. https://doi.org/10.1016/j.esr.2013.02.001.

[29] Hvelplund F, Østergaard PA, Meyer NI. Incentives and barriers for wind power expansion and system integration in Denmark. Energy Policy 2017;107:573–84. https://doi.org/10.1016/j.enpol.2017.05.009.

[30] Mendonça M, Lacey S, Hvelplund F. Stability, participation and transparency in renewable energy policy: Lessons from Denmark and the United States. Policy Soc 2009;27:379–98. https://doi.org/10.1016/j.polsoc.2009.01.007.

[31] Cludius J, Hermann H, Matthes FC, Graichen V. The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: Estimation and distributional implications. Energy Econ 2014;44:302–13. https://doi.org/10.1016/j.eneco.2014.04.020.

[32] Azofra D, Jiménez E, Martínez E, Blanco J, Saenz-Díez JC. Wind power merit-order and feed-in-tariffs

effect: A variability analysis of the Spanish electricity market. Energy Convers Manag 2014;83:19–27. https://doi.org/10.1016/j.enconman.2014.03.057.

[33] Woo CK, Moore J, Schneiderman B, Ho T, Olson A, Alagappan L, et al. Merit-order effects of renewable energy and price divergence in California's day-ahead and real-time electricity markets. Energy Policy 2016;92:299–312. https://doi.org/10.1016/j.enpol.2016.02.023.

[34] Sensfuß F, Ragwitz M, Genoese M. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 2008;36:3086–94. https://doi.org/10.1016/j.enpol.2008.03.035.

[35] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy 2009;34:524–31. https://doi.org/10.1016/j.energy.2008.04.003.

[36] Mathiesen BV, Lund H, Karlsson K. 100% renewable energy systems, climate mitigation and economic growth. Appl Energy 2011;88:488–501. https://doi.org/10.1016/j.apenergy.2010.03.001.

[37] Rodríguez RA, Becker S, Andresen GB, Heide D, Greiner M. Transmission needs across a fully renewable European power system. Renew Energy 2014;63:467–76. https://doi.org/10.1016/j.renene.2013.10.005.

[38] Varian, Hal. Intermediate Microeconomics. 7th Edition. W.W. Norton & Company; 2006.

[1] Energinet.dk. Udtræk af markedsdata 2018. http://energinet.dk/DA/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx.

[40] Sustainable Energy Planning Research Group Aalborg University. EnergyPLAN | Advanced energy systems analysis computer model 2017.

[41] Lund H, Thellufsen JZ, Mathiesen BV, Østergaard PA, Lund R, Ridjan I, et al. EnergyPLAN - Documentation Version 13. 2017.

[42] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33. https://doi.org/10.1016/j.apenergy.2015.05.086.

[43] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Appl Energy 2011;88:502–7. https://doi.org/10.1016/j.apenergy.2010.03.006.

[44] Cerovac T, Ćosić B, Pukšec T, Duić N. Wind energy integration into future energy systems based on conventional plants – The case study of Croatia. Appl Energy 2014;135:643–55. https://doi.org/10.1016/j.apenergy.2014.06.055.

[45] Østergaard PA, Lund H, Mathiesen BV. Energy system impacts of desalination in Jordan. Int J Sustain Energy Plan Manag 2014;1:29–40. https://doi.org/10.5278/ijsepm.2014.1.3.

[46] Xiong W, Wang Y, Mathiesen BV, Lund H, Zhang X. Heat roadmap China: New heat strategy to reduce energy consumption towards 2030. Energy 2015;81:274–85. https://doi.org/10.1016/j.energy.2014.12.039.

[47] Waenn A, Connolly D, Gallachóir BÓ. Investigating 100% renewable energy supply at regional level using scenario analysis. Int J Sustain Energy Plan Manag 2014;3:21–32. https://doi.org/10.5278/ijsepm.2014.3.3.

[48] Brandoni C, Arteconi A, Ciriachi G, Polonara F. Assessing the impact of micro-generation

technologies on local sustainability. Energy Convers Manag 2014;87:1281–90. https://doi.org/10.1016/j.enconman.2014.04.070.

[49] Hagos DA, Gebremedhin A, Zethraeus B. Towards a flexible energy system – A case study for Inland Norway. Appl Energy 2014;130:41–50. https://doi.org/10.1016/j.apenergy.2014.05.022.

[50] Lund R, Mathiesen BV. Large combined heat and power plants in sustainable energy systems. Appl Energy 2015;142:389–95. https://doi.org/10.1016/j.apenergy.2015.01.013.

[51] Lund R, Ilic DD, Trygg L. Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark. J Clean Prod 2016;139:219–29. https://doi.org/10.1016/j.jclepro.2016.07.135.

[52] Lund H. Excess electricity diagrams and the integration of renewable energy. Int J Sustain Energy 2003;23:149–56. https://doi.org/10.1080/01425910412331290797.

[53] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's Energy Vision 2050 – Technical data and methods. 2015.

[54] Danish Energy Agency Energinet.dk, Danish Energy Authority, Energinet.dk. Technology Data for Energy Plants. vol. 978-87–784. 2016. ISBN: 978-87-7844-857-6.

[55] Energinet.dk. Udtræk af markedsdata 2018. http://osp.energinet.dk/_layouts/Markedsdata/framework/integrations/markedsdatatemplate.aspx

[1

Highlights

- Calculates electricity prices in a renewable energy system with current market design.
- Calculates private profitability of wind power investments within such system.
- The market design cannot financially sustain wind power in a renewable energy system.