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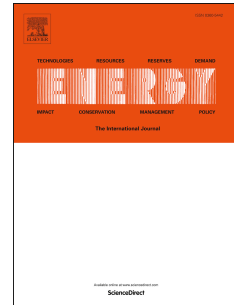
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# The Electricity Market in a Renewable Energy System

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## 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

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32 CHP3: Centralised combined heat and power plants

33 PP: Power plants

34 VRES: Variable Renewable Energy Sources

35 DK1: Western Denmark

36

## 37 1 Introduction

38 The radical change of traditional fossil fuel-based energy systems to systems based on variable renewable  
39 energy sources involves both technical and institutional challenges. In the transition towards 100%  
40 renewable energy systems, one suggested pathway is the smart energy system (SES) [1–4]. Smart energy  
41 systems rely on three main components: smart electricity grids, smart thermal grids, and smart gas grids  
42 [5]. These main components are all interconnected to achieve the most efficient solutions to the  
43 integration of variable renewable energy sources (VRES).

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

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

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

68 Common for these studies is that they investigate the technical operation of the energy system. Together  
69 they create a framework where the goal is to lower the fuel consumption. This article takes point of

70 departure in the technical scenarios developed within the SES framework. Studies have shown the technical  
71 and economic feasibility of such systems [15,26]. The central economic question regarding SES, thus, has an  
72 institutional and organisational character [9,27–30]. A pertinent question is: to what extent current market  
73 structures can support the massive increase in variable renewable energy capacities that are the main  
74 pillars of future SES?

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

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

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

## 94 2 Current market structures: The merit order effect in theory and 95 practice

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

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

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

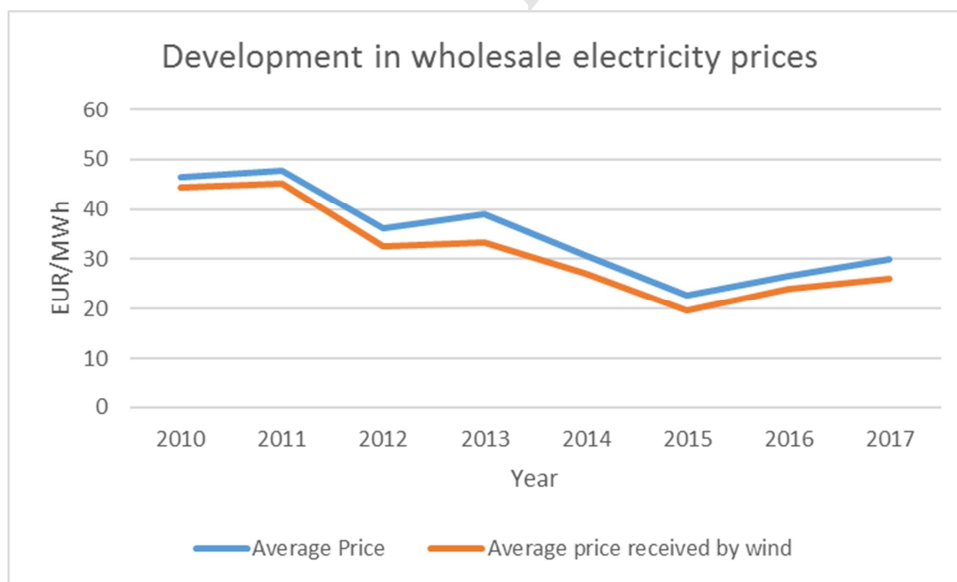
108 Having no fuel consumption, wind power, and photovoltaics have no marginal costs within such a market  
 109 structure. The effect of this is well known in the literature and is usually referred to as the merit order  
 110 effect [28,31–34, 39].

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

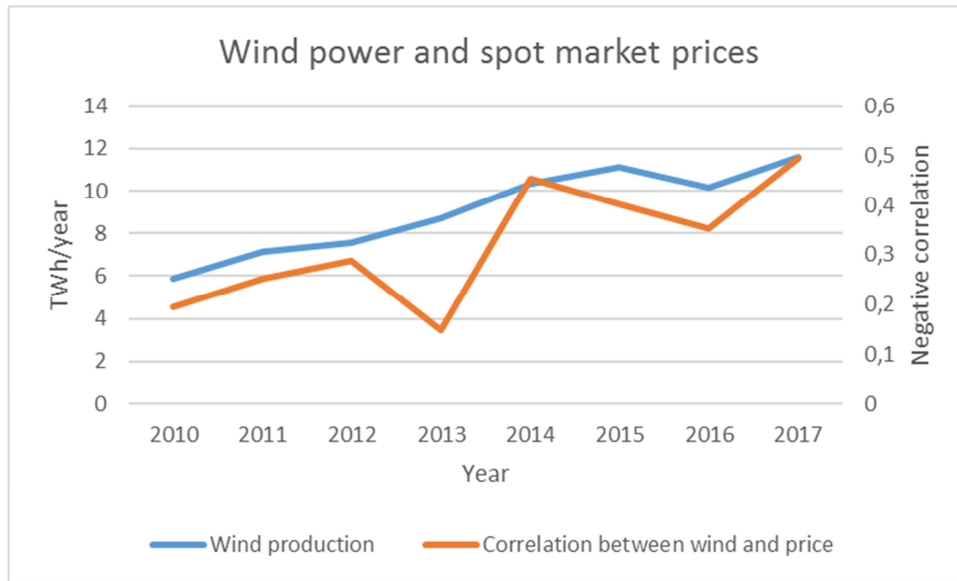
114 The existence of the merit order effect is observed in several publications. It is well described how the  
 115 introduction of wind, photovoltaics, and other alike technologies will lead to declining market prices when  
 116 introduced in the current market structures [28, 31–34, 39].

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

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



128  
 129 **Fig. 1.** The development in spot market prices in Western Denmark (DK1).

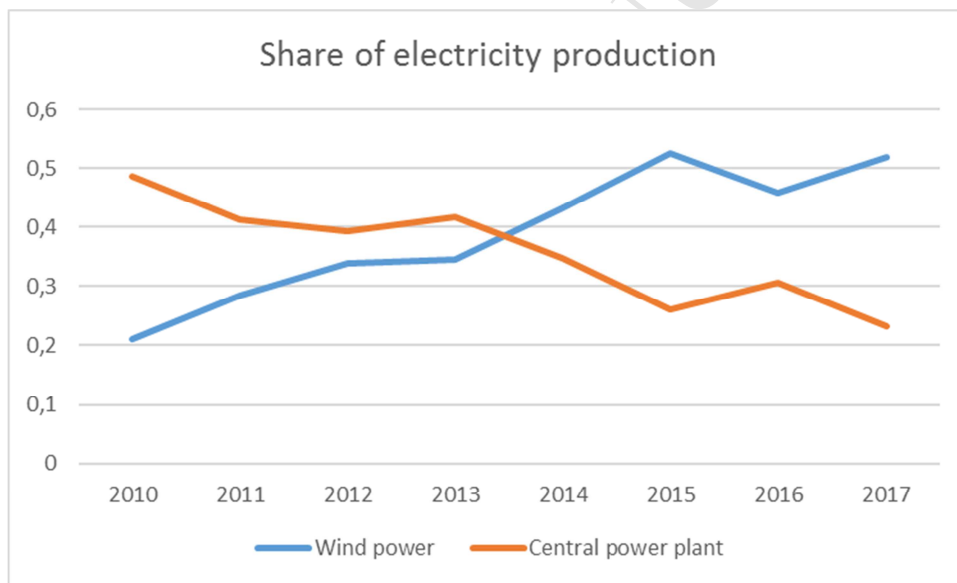


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**Fig. 2.** Development in wind power production and the correlation between wind production and market prices in Western Denmark (DK1).



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

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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.

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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

144 more connected to long-term capital costs, and less related to short-term fuel costs, institutional structures  
145 addressing the short-term costs become less influential to the total system costs.

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

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

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

### 161 3 Methods

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

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

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

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

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

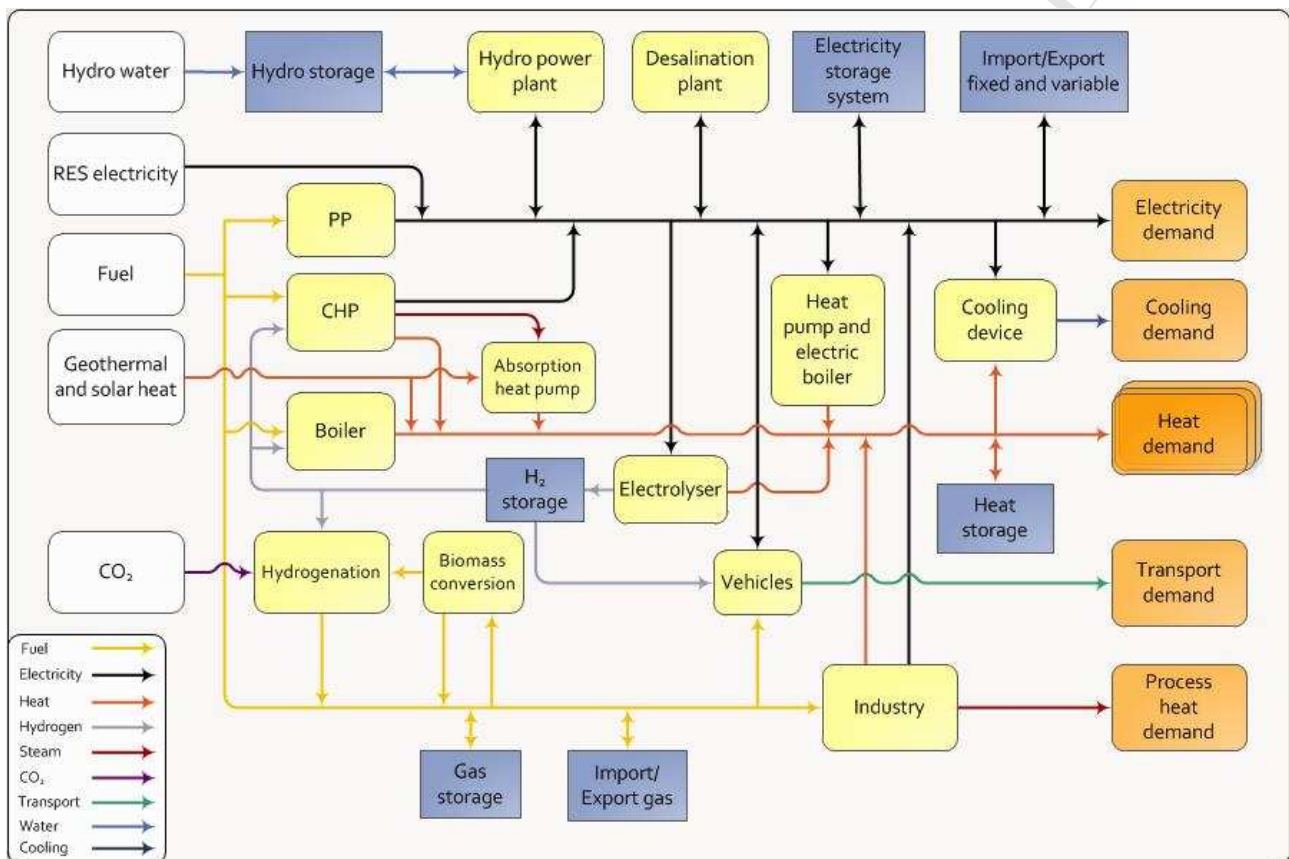
198 EnergyPLAN models the heating sector as two different types of demands: either an individual heated  
199 building or buildings connected to district heating. The individual heated building, in this case, operates on  
200 heat pumps and biomass boilers and, therefore, results in either an increased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

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

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

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

230



231

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

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

239 The first step of the analysis is to simulate the operation of the scenario from 'IDA's Energy Vision 2050'.  
 240 The 2050 scenario is used, which is simulated based on the technical simulation strategy, achieving a fuel-  
 241 efficient operation of the entire energy system. The scenario is based on a range of different potential  
 242 future fuel costs. The scenarios are run exactly as they are described in 'IDA's Energy Vision 2050', meaning

243 they rely 100% on renewable energy and an integrated energy system utilising heat storages, gas storages,  
 244 heat pumps, and power-to-gas. Also, flexible electricity demands and electric vehicles with smart charge  
 245 technology are implemented. Since the primary source of energy is wind power, this is the main emphasis  
 246 of the analysis. Table 1 shows installed capacity of VRES. For comparison, the annual electricity  
 247 consumption is 94.11 TWh in the 2050 scenario. This also shows why this study emphasises onshore wind  
 248 power and offshore wind power, as these are the main producers of energy, not only in the electricity  
 249 sector but in the entire energy system.

250 **Table 1**

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

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

253

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

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

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

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

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

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

$$286 \quad M_{cost} = F_{cost} + VO\&M_{cost} \quad (1)$$

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

292 **Table 2**

293 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

294

295 **Table 3**

296 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

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

297

298 **Table 4**

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

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

300

301 By combining the knowledge of exactly how the 100% renewable energy system operates in each hour of  
 302 the year, what the marginal producing unit is in every hour, and what the cost is of operating that unit, it is  
 303 possible to find the electricity market price and the resulting annual income for wind turbines. These  
 304 earnings are compared with the investment costs for the onshore and offshore wind turbines, respectively.  
 305 Here, the study uses two different assumptions for investment costs and fixed operation and maintenance  
 306 costs. The first scenario is based on current 2015 prices, while the second scenario is based on assumed  
 307 2050 prices. Both price scenarios are from the Danish Energy Agency [54]. Table 5 shows the cost scenarios  
 308 for onshore and offshore wind turbines.

309 **Table 5**

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

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

311

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

## 319 4 Results

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

327 **Table 6**

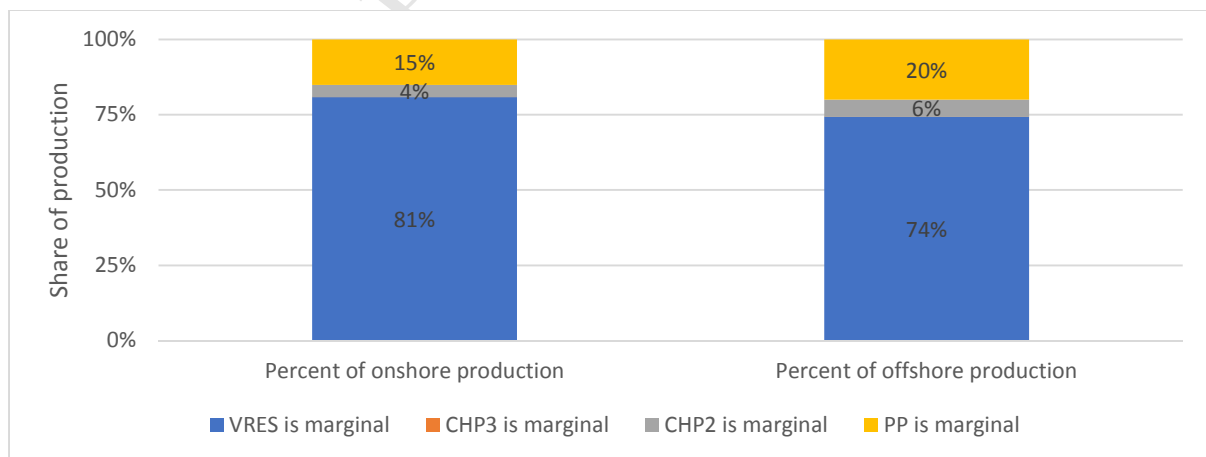
328 Number of hours where different technologies set the marginal price.

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%

329

330 The financial challenge for wind energy investments becomes clearer when looking at the energy amounts  
 331 produced from various technologies. In the simulation, most of the yearly wind production occurs in hours  
 332 where VRES are the marginal producer. Fig. 5 illustrates this by comparing the energy production from the  
 333 different units in every hour with the marginal producer. Fig. 5 also shows that for onshore wind turbines,  
 334 81% of its energy production is sold at zero prices; in other words, hours where a variable renewable  
 335 energy technology is the marginal producer, 74% of the offshore wind production hours occur at a zero  
 336 price. Onshore wind turbines, therefore, only receive an income on 19% of their supplied energy to the  
 337 system. For offshore wind turbines the income situation is slightly better, with 26% of their energy traded  
 338 in hours where a fuel-fired plant is the marginal supplier.

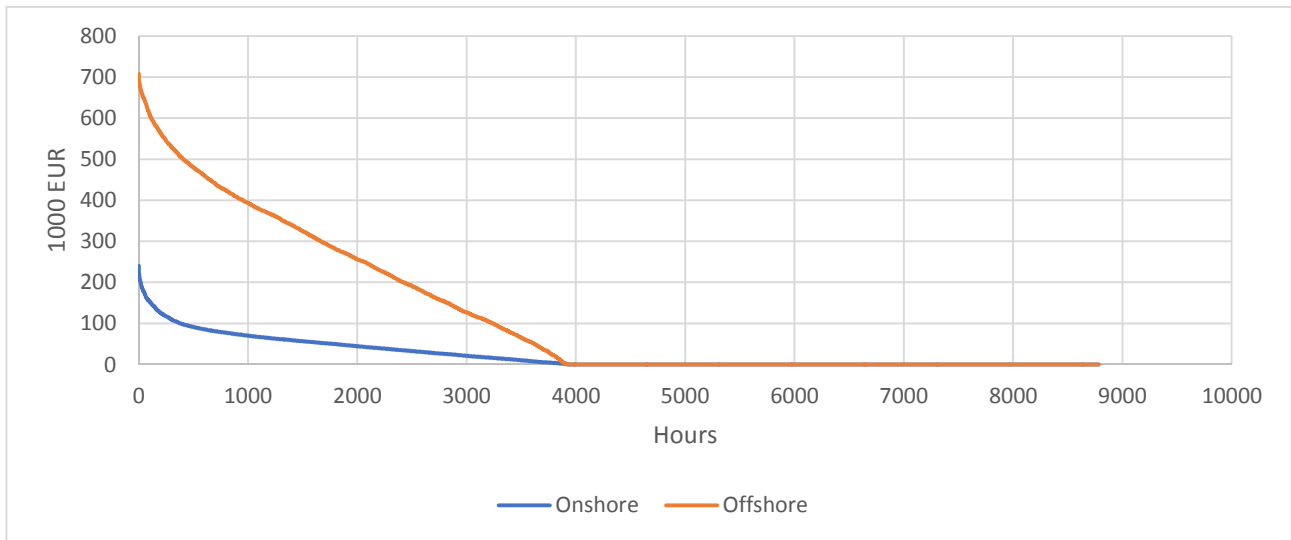
339



340

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

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



347  
 348 **Fig. 6.** Duration curve of the income on the installed onshore and offshore wind turbines in a medium fuel price scenario.

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

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

369 This points to the conclusion that complementary institutions, such as feed-in tariffs, or a more  
 370 fundamental restructuring of the electricity market design is necessary for providing sufficient VRES in a  
 371 100% renewable energy system.

372

373 **Table 6**

374 Internal rate of return for onshore wind.

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

375

376 **Table 7**

377 Internal rate of return for offshore wind.

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

378

## 379 4.1 Discussion of key methodological choices

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

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

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

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

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

402 Second, there is an assumption of full competition on the supply side. This means that it is assumed that  
403 prices strictly reflect marginal production costs. Weakened competition among suppliers may clearly allow

404 marginal producers to charge above marginal costs and, thereby, raise price levels. However, since market  
405 structures, such as the Nord Pool Spot market, is designed with the assumption of full competition, it is  
406 appropriate to evaluate these markets structures with the assumption of full competition. In other words,  
407 we assume the markets to work as they are designed to work.

## 408 5 Conclusions

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

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

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

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

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

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

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

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

452

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

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

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

464

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**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.

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