Energy 151 (2018) 94–102

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach

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A R T I C L E I N F O

*Article history:*
Available online 3 March 2018

*Keywords:*
Smart energy systems
Smart grid
Energy infrastructures
Energy storage
Heat scenarios
Renewable energy

## ABSTRACT

This paper compares different strategies to transform the heating sector into a future 100% renewable energy solution. It focuses on the consequences for infrastructures in terms of grids and storage across the electricity, gas and heating sectors. The hypothesis is that these consequences are rarely taken into proper consideration, even though the costs are significant and differ substantially between the alternative pathways. While the smart grid scenarios are based on electricity as an energy carrier, the "smart energy systems" approach is based on a cross-sectoral use of all grids. Using Denmark as a case, this paper shows how the current gas and district heating grids each have twice the capacity of the electricity distribution grid. Moreover, the existing gas and thermal storage capacities are substantially higher and the additional future capacities are more affordable than within the electricity sector. The conclusion is that the "smart grid" pathway requires a 2–4 times expansion of the electricity grid and significant investments in electricity storage capacities, while the "smart energy systems" pathway can be implemented with relatively few investments in affordable minor expansions of existing grids and storage capacities.

## 1. Introduction

The thermal sector currently accounts for 50% of Europe's final energy consumption [1]. This makes heating and cooling Europe's biggest energy sector and it is expected to remain so for the foreseeable future [1]. At the same time, the potential for improvement is substantial. It has been calculated that waste heat from Europe's industry and electricity production exceeds the heat demand of all buildings in Europe [2]. Consequently, this is a key-sector to address in order to meet the goals of Europe expressed in the energy union. Furthermore, the thermal sector has a unique potential for decreasing fossil fuel consumption and $CO_2$ emissions in Europe (and elsewhere), while simultaneously decreasing costs and creating jobs [2].

Often, analyses of the transition to future sustainable energy systems are based on scientific approaches that are limited to certain sub-sectors of the energy system [3]. The smart grid concept [4] is typically defined and applied within the limitations of the electricity sector, thus creating a paradigm in which solutions to the integration of fluctuating renewable energy should be found within the sub-sector itself [5]. This is the case no matter if the smart grid focus is on storage [6], electric vehicles [7] or information systems [8]. The concept of power-to-gas [9] is defined mostly to boost hydrogen [10] and/or green gas [11] and green liquid fuel [12] productions within the limitations of the gas and electricity sectors. The concept of NZEB (Net Zero Energy Buildings) [13] as well as related concepts such as ZEB [14], Nearly-zero [15] and LC-ZEB [16] is defined within the limitations of the building sector and with a focus on new buildings [17]. These, as well as similar technological and infrastructural concepts, are essential, new contributions, and represent an important paradigm shift in the design of future sustainable energy strategies. However, they are all sub-systems and sub-infrastructures which cannot be fully understood or analysed if not properly placed in the context of the overall energy system. Moreover, potential interaction with the industrial sector [18] including surplus heat [19] and CO2 reductions [20] as well as low temperature [21] and urban [22] heating and cooling sectors [23] has largely been overlooked [24].

If integrated properly with the other sub-sectors, the thermal sector has the potential to provide feasible, least-cost solutions for

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https://doi.org/10.1016/j.energy.2018.03.010

the integration and storage of variable renewable energy sources such as wind, PV and wave power, and is the key to establishing the cross-sectoral smart energy systems approach. The 2016 EU strategy on Heating and Cooling [1] emphasizes how district heating and cooling can integrate renewable energy and offer flexibility to the energy system by storing thermal energy at low cost. However, if these benefits are to be realized in member states, it calls for strategies to quantify all benefits and compare these with relevant alternatives.

This paper compares different strategies to transform the heating sector into a future 100% renewable energy solution. It compares several “smart grid” strategies based on electric heating and individual heat pumps against a “smart energy systems” strategy based on integrating district heating with the other sub-sectors. The focus is on the consequences for infrastructures in terms of grids and storage across the electricity, gas and heating sectors. The hypothesis is that these consequences are rarely taken into proper consideration, even though the costs are significant and differ substantially between the alternative pathways.

As further detailed in Ref. [25], the concept of smart energy systems was introduced in order to identify the potential synergies between sub-sectors. The hypothesis is that the most effective and least-cost solutions are found when each sub-sector is combined with the other sectors. One main point is that the analysis of individual technologies and sectors are contextual and, to do a proper analysis, one has to define the overall energy system in which the infrastructure should operate. Another main point is that different sub-sectors influence one another and one has to take such influence into consideration if the best solutions are to be identified.

The term Smart Energy or Smart Energy Systems was defined and used in order to provide the scientific basis for a paradigm shift away from single-sector thinking and towards a coherent and integrated understanding of how to design and identify the most achievable and affordable strategies to implement coherent future sustainable energy systems. This way of using the term Smart Energy Systems was first introduced in 2012 [26]. It was later given a specific definition published in a book in 2014 [3] after being pre-published in a booklet from 2013 [27].

Finally, this study is based on the theory and understanding that the analysis of future sustainable energy solutions at the national level should be carried out so that any resulting recommendations are designed to enter into a democratic process. As further detailed in Ref. [28], the type of democratic process generated during public controversies over techno-scientific issues is important, because new hybrid forums may organize deliberative processes in which heterogeneous actors from affected groups collectively deal with problems in which they are all implicated.

## 2. Methodology and tool

This paper takes its point of departure in two studies concerning future strategies for the conversion of the Danish heating sector into a solution based 100% on renewable energy. These two studies are based on the philosophy of a smart energy systems approach, i.e., that the heating sector should be an integrated part of the rest of the system and that the best solutions can be found only when there is a focus on how the different sectors may assist one another, as already mentioned in the introduction.

The first study is the Future Green Buildings study [29], which focuses on the heating of buildings. The report aims to first strike a balance between supply and demand (i.e. how much effort should be put into savings and conservation in buildings), and second, to find a balance between district heating and individual building supply. The report is based on the result of a number of previous studies [30,31]. Fig. 1 shows the recommendations of the report. The investment costs of implementing the proposed savings measures are estimated at 30 Billion EUR [32,33].

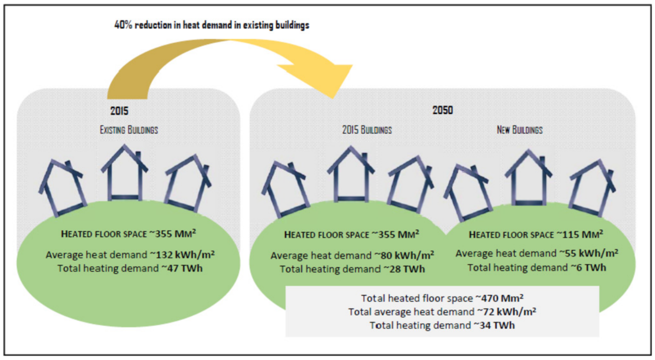

**Fig. 1.** A suitable strategy for future buildings in a Danish 100% renewable energy scenario based on the identification of a least-cost balance between savings and supply as detailed in the following sources [29].

The next study is the IDA Energy Vision Report [33]. In this report, a heating strategy similar to the one illustrated in Fig. 1 is integrated into a coherent 100% renewable solution involving all sectors based on a smart energy systems approach. The smart energy systems approach makes use of all existing grids and energy storage capacities.

In this paper, the idea is to compare such a smart energy systems strategy with one that relies on using only the electricity grid and infrastructures as the sole backbone for also affecting the heating sector. The latter strategy is heretofore called a smart grid strategy. It should be emphasized that several scenarios and variants exist which could all be referred to as smart grid strategies since this term is not completely well defined [3]. However, for practical reasons, only a few variants are described here. The idea is to identify and quantify the consequences for storage and grid infrastructures within both approaches.

The modelling of the consequences of the different sustainable heat scenarios and strategies has been carried out using the advanced energy system analysis tool EnergyPLAN (version 13) [34,35]. The choice of such tool has the following benefits:

- The calculations can be **replicated by other researchers**. The EnergyPLAN tool is a freeware, which can be downloaded from the homepage www.EnergyPLAN.eu. The model is free of charge and comes in a user-friendly Windows application. It can operate on a normal computer and it does not depend on any additional solvers or similar. Moreover, all the input data used in this study have been up-loaded to the same homepage and can be downloaded freely.
- The tool has a **high degree of credibility**. A full and up-dated documentation of the tool can be downloaded from the abovementioned homepage. The model is widely used with more than 5000 downloads from more than 100 different countries around the world (primo 2017). Moreover, the tool forms the basis for research documented in more than 100 peer-reviewed research articles [36] and has been used for energy systems models at the European level [2,37] as well as at the national level for a number of countries such as Romania [38], Ireland [39], Croatia [40], Jordan [41], China [42–44], Serbia [45], Finland [46] and Denmark [47].
- The tool allows for energy system models that align with the **Smart Energy Systems** theory and concept [3,26]. Thus, the tool allows for models that include all relevant sectors of a national energy system (Buildings, Industry, Transportation, etc.) as well as all relevant energy carriers and related grid and storage

options (Electricity, District Heating and Cooling, Hydrogen, Green gas, solid biomass and synthetic green liquid fuels). Moreover, it includes a long list of conversion units between the different energy forms in question [35].

- **The tool allows for high time resolution and chronological calculations of storage and grid infrastructures.** The model accounts for energy balances for all components for an entire year using hourly time-steps. Of particular importance to this study is that the tool chronologically calculates hourly inputs, outputs and contents of all storage capacities. Thus, the model can hour by hour account for the use of all types of energy storage in the system.

More details on the EnergyPLAN tool in comparison to other models are presented in Ref. [48] and a detailed documentation and description of the model can be found in Refs. [3,49]. Moreover, discussions and descriptions can be found on how the tool applies to the concept of smart energy systems [25]. Theoretical considerations concerning optimisation versus simulation tools are presented in Ref. [28] and the problem of uncertainties in future fuel and electricity prices is described in Ref. [50].

## 3. Modelling, data and assumptions

In particular, the data regarding existing grids and storage capacities as well as the costs related to their potential expansion are essential for this study. Unfortunately, these data - especially with regard to the grids - are generally not well known nor thoroughly reported. Consequently, extensive efforts have been carried out to identify them as part of this study as further explained in the following sections and in a small independent appendix [51].

### *3.1. The Danish electricity, gas and district heating distribution grid infrastructures*

In this study, the capacities of existing distribution grid infrastructures are described according to their proven capacity, i.e., how much energy has been delivered to consumers in a peak hour.

For the Danish electricity distribution grid, such peak hour value is measured by the Danish TSO and has stayed at approx. 6000 MW for the last decade [52].

In terms of Danish gas distribution, domestic consumption peaked in 2010 with approx. 25 million Nm3 per day, equal to 12,500 MW [53]. The hourly peak is around 10% higher than the daily average [54], resulting in a proven hourly maximum capacity of approx. 14.000 MW.

The Danish district heating grid consists of 300–400 separate grids, of which a few of the large systems are connected by transmission lines. Hourly peak demand measurements exist for some of the systems, but there is no coordinated measurement to detail the exact maximum hourly deliverance of all systems at any one time. In accordance with Danish Energy Statistics [53], the maximum annual demand in recent years appeared in 2010, which was a relatively cold year in Denmark. In 2010, the demand for district heating was 150,393 TJ [53], equal to 41.8 TWh or an average of 4800 MW. Based on a typical hourly distribution and duration curve (which is used and detailed later), with a correlation factor of 2.81 between the average and peak, the proven capacity of the Danish district heating grid can be estimated at approx. 13,000 MW.

The proven capacities of the three distribution grids are shown in Fig. 2. As seen, both the gas and district heating grids are 2–3 times higher in proven capacity than the electricity grid.

It should be added that Denmark also has District Cooling grids and they are being expanded. However, compared to the other grids, the current capacity is very low. For example, the capacity of the District Cooling grid in Copenhagen is below 100 MW.

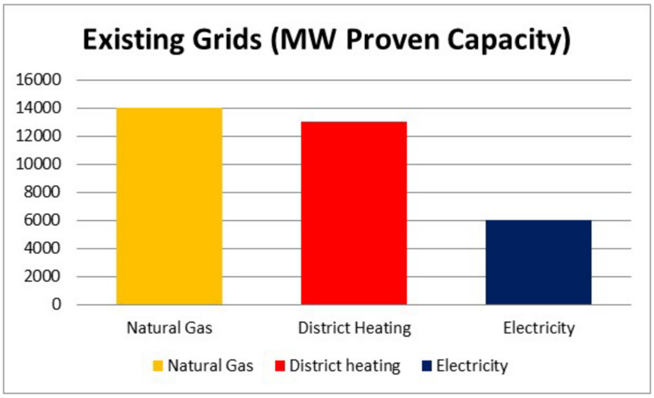

**Fig. 2.** Comparison of the proven capacity of Danish distribution grids.

An estimate of the current value and potential cost of expanding the electricity distribution grid in Denmark reaches the conclusion that minor increases in demand can be achieved with minor investments, while a doubling or more of demand would require investments similar in size to the grid's entire current capital value. However, it is difficult to conclude how much is fixed costs of having a grid and how much is variable to the size of the grid. For such reason, two curves have been made assuming a fixed cost of 5 and 10 Billion EUR/MW respectively, and relative costs so that in both cases the cost of the current distribution grid is 20 Billion EUR/MW. The estimate is detailed further in Ref. [51] and results in the cost-curves shown in Fig. 3.

While the expansion of the electricity grid (in this study) represents a general increase in supply and is relative to the peak-load, the district heating distribution grid presents a different situation. The various district heating grids connect to approx. 50% of the consumers in Denmark and an expansion will involve new connections to the remaining houses. Due to the remoteness of many buildings, typically, the more buildings one connects, the higher per unit price. The Danish Technology catalogue lists the cost of a complete grid in terms of EUR per MWh/year: the cost varies from 150 in dense urban areas to 700 in new areas with attached houses.

Based on these numbers and further considerations detailed in Ref. [51], a cost curve is made, as shown in Fig. 4. The value of the current grid is found to be 15 billion EUR and its expansion is based on the estimates of the study "Heat Plan Denmark" from 2008 [55]. However, to adjust the costs in the study from 2008 prices to today, all numbers are increased by 20%. It should be noted that costs for expanding beyond a 70% coverage rate are not accurate. These are added just to imply that after this point the costs will increase

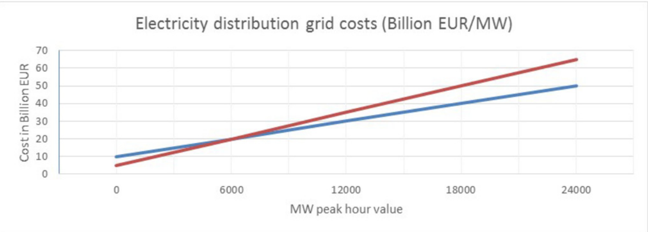

**Fig. 3.** An estimate of investment costs in electricity distribution grids as a function of the peak load in MW. The current Danish grid represents a peak load of 6000 MW, corresponding to an investment of 20 Billion EUR. Since it is difficult to conclude how much is fixed costs of having a grid and how much is variable to the size of the grid, two curves have been made assuming a fixed cost of 5 and 10 Billion EUR/MW respectively.

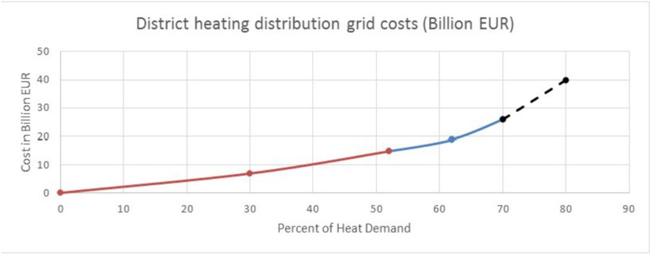

**Fig. 4.** An estimate of investment costs in district heating distribution grids as a function of the percentage of Danish heat demand covered. The current grid in Denmark represents an annual average demand of approx. 35 TWh/year, corresponding to an investment of 15 Billion EUR.

significantly.

### 3.2. Existing and potential Danish energy storage infrastructures

At the national level, existing energy storage capacities in Denmark involve liquid fuel storage in the form of oil tanks, two central natural gas storages and a number of thermal storage capacities connected to the district heating supply as well as hot water tanks in individual households. Of these storage capacities, the oil tanks are by far the largest, totalling approx. 50,000 GWh [56].

The Danish Natural gas supply involves two large gas storage facilities located in Ll. Thorup in Jutland and Stenlille in Sealand. Historically, these storages are charged during summer and decharged during winter. The total gas storage capacity of Ll. Thorup and Stenlille is approx. 1 billion Nm3, equal to 11,000 GWh. Losses from these storages are negligible.

The thermal heat storage capacity is substantially lower and includes large steel water tanks in connection to district heating plants as well as seasonal storage in connection to large solar thermal plants. Additionally, one may include the many hot water tanks in each building. However, by far, the major thermal storage capacity is provided by the water in the grid itself.

The district heating system itself serves as a thermal storage, since certain district heating companies sometimes increase the system temperature prior to the morning hourly peak. In total, there is around 450 million $m^3$ of water in the various Danish district heating systems. A rough estimate of the potential thermal storage capacity of the grid, assuming that half of the water in the network (not including the return) can be increased by 10 °C, leads to a resulting thermal storage capacity of 2600 GWh.

The capacity of consumer-owned hot water tanks is much lower. An estimate of individual storage capacity is calculated based on the assumption that 2 million homes have an average water tank capacity of 150 L. This equates to 300,000 $m^3$, or approx. 20 GWh thermal storage capacity, assuming a temperature difference between when den storage is full and empty of 60 °C.

The capacity for district heating steel tanks for water in 2013 was found to be 875,000 $m^3$, equal to a thermal capacity of approx. 50 GWh [57]. The price level is described as 1000 DKK/$m^3$, equal to around 2300 EUR/MWh and the lifetime is 40 years. In the same report, large seasonal thermal storage for solar thermal in Denmark consists of the following [57]:

- Pit-storage in Ottrupgård (1993–95) of 1500 $m^3$, equal to 43.5 MWh.
- Pit-storage in Marstal (2003) of 10,000 $m^3$, equal to 638 MWh.
- Pit-storage in Marstal (2011–12) of 75,000 $m^3$, equal to 6960 MWh
- A BTES in Brædstrup (2011–12) of 19,000 $m^3$ (soile), equal to 630 MWh
- Pit-storage in Dronninglund (2016) of 60,000 $m^3$, equal to 5570 MWh.

In total, these result in a capacity of approx. 14 GWh. These storage facilities are estimated to have an investment cost of approx. 3000 DKK/MWh, equal to 400 EUR/MWh.

An overview of existing energy storage capacities in Denmark is given in Fig. 5.

The existing electricity storage capacity in Denmark is negligible. To illustrate this, consider the potential scenario in which electric cars with a battery capacity of 30 kWh replaced all 2.5 million vehicles in the country. This considerable change would sum up to a total of only 75 GWh storage capacity, which is quite small compared to the capacities mentioned above. Denmark does not have conditions for pumped hydro or similar. However, if it is looked at from a European level, one may argue that Denmark could expect to use its share of the total hydro power storage capacity. The maximum storage capacity in Europe (mostly located in Norway) is approx. 120 TWh [58], and the Danish share of the European electricity demand is approx. 1%, leading to a Danish share of 1200 GWh. Still, one must remember that most of this capacity is already used to level out seasonal variations in the inflow of water. These electricity storage potentials are shown in Fig. 6.

The cost of storage technologies and renewable energy is based on appendix 1 in the paper “Energy Storage and Smart Energy Systems” [59]. These investment costs correspond well with the Danish energy technology catalogue [60] as well as the costs

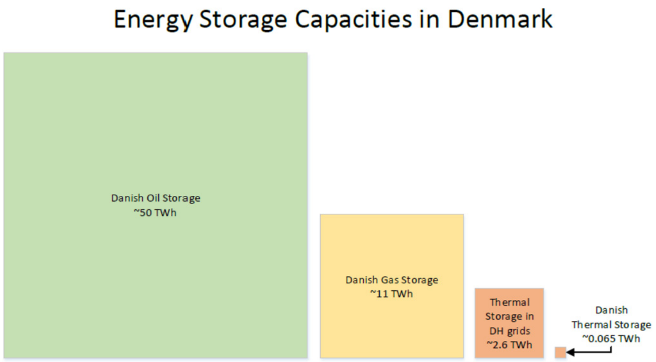

**Fig. 5.** Overview of existing energy storage capacities in Denmark.

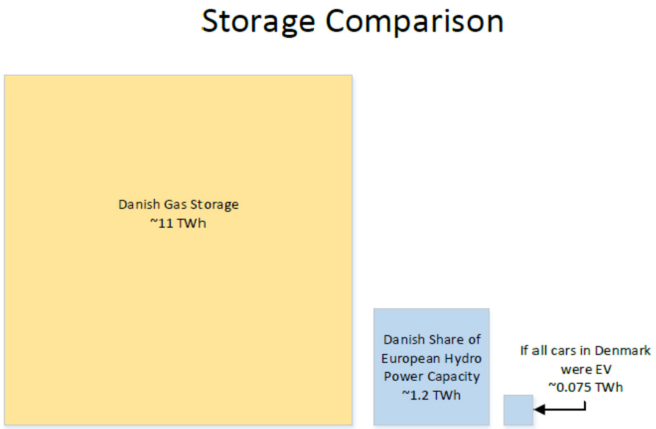

**Fig. 6.** Illustration of potential electricity storage capacities.

mentioned above with regard to thermal storage. Moreover, these costs have been supplemented with those of a few other relevant technologies, mainly based on [33].

To fit the broad analytical goals of this paper, the costs have been grouped into the categories shown in Tables 1–3.

### 3.3. Hourly data

As mentioned in the methodology section, this study is based on detailed hourly calculations using the EnergyPLAN model. Fig. 7 shows the hourly data for renewable energy and heat demands, which are the most important hourly input data for this study.

The capacity factor of wind is based on the variation of the actual wind production in western Denmark in 2016; however, this is adjusted to a future capacity factor of 0.43. Similarly, the capacity factor of PV is based on the variation for 2001 (because of available data) and is then adjusted to a capacity factor of 0.14.

The duration in heat demand is based on a typical district heating variation including hot water, space heating and grid losses. When used for individual heating, the grid loss is subtracted, and when used for the scenarios with savings, the space heating demand is reduced accordingly. Fig. 7 shows the variation for individual heating without savings.

## 4. Analysis and results

As illustrated in Fig. 1, the Danish Heat Demand in 2015 was 47 TWh/year. With no savings, it is expected to be 53 TWh/year in 2050. With savings (as suggested in the future green buildings report), it will be 34 TWh/year in 2050, of which 28 TWh/year concerns existing buildings. The following calculations are based on the current heat demand of 47 TWh/year and the potential of reducing it to 28 TWh/year. In accordance with [33], the investment costs of such a reduction are found to be 30 billion EUR if the savings are implemented over a certain period and coordinated with normal renovations.

Based on these heat demands, the following alternatives have been designed to analyse the consequences of seeking solutions based solely on the electricity system (smart grid approach) and solutions based on an integrated cross-sectoral use of primarily existing infrastructures (smart energy systems approach).

### 4.1. Alternative 1: individual electric heating ("smart grid")

In the first alternative, all heating is based on individual electric heating in all buildings. This solution requires approx. 12,500 MW wind power to produce the corresponding electricity demand of 47 TWh/year and increases the peak electricity load by more than 17,000 MW, from 6000 MW to almost 24,000 MW. However, due to the variable nature of wind power, it is necessary to match the hours of heat demand with the expected hours of wind energy production. Of the 47 TWh/year wind produced electricity, approx. 14–15 TWh/year will not match up with the hours of heat demand. In order to make a perfect hourly match, an electricity storage capacity of 15,000 MW and approx. 10 TWh would be required. Moreover, to cover for losses in this storage, an additional wind power production of 3.4 TWh/year would be needed, equal to a capacity of 800–900 MW. In this alternative, the total cost of increased wind turbine capacity is approx. 25 billion EUR. The cost of the increase in electricity distribution grids amounts to 30–45 billion EUR and the total cost of electricity storage is 2000 billion EUR.

**Table 1**
Storage cost assumptions.

| Storage type | Investment range [EUR/MWh] | Investment (chosen in this study) [EUR/MWh] | O&M [Percent of investment] | Lifetime [Years] | Cycle efficiency |
|---|---|---|---|---|---|
| Large electricity storage (PHS) | 125–600,000 | 200,000 | 0.5 | 100 | 0.8 |
| Household electricity storage (Tesla) | 600,000 | 300,000[a] | 0.5 | 20 | 0.8 |
| Large thermal storage | 500-2500 | 1500 | 0.5 | 40 | 0.9 |
| Household thermal storage | 24,000–180,000 | 20,000[a] | | 30 | 0.9 |
| Large gas storage | | 60 | | 50 | 1.0 |
| Liquid fuel | | 20 | | 30 | 1.0 |

[a] In this paper's scenarios, the storage capacities are higher than expressed in the costs. Consequently, the per unit cost has been reduced to express a certain economy of scale.

**Table 2**
Renewable electricity cost assumptions.

| Renewable Energy type (expected anno 2030) | Investment [MEUR/GW] | Technical lifetime [Years] | Capacity factor | O&M [EUR/MWh] |
|---|---|---|---|---|
| Wind (a combination of onshore and offshore) | 1800 | 25 | 0.43 | 14 |
| PV (grid connected) | 800 | 40 | 0.14 | 7 |

**Table 3**
Heat production cost assumptions.

| Renewable Energy type (expected anno 2030) | Investment [MEUR/TWh heat] | Technical lifetime [Years] |
|---|---|---|
| Electric heating | 100 | 30 |
| Central Heating | 200 | 30 |
| Individual heat pumps | 1000 | 15 |
| Largescale heat pumps | 400 | 25 |
| Solar Thermal – individual | 1500 | 20 |
| Solar Thermal – largescale | 300 | 25 |
| Recycling of heat | 150 | 30 |
| Peak load biomass boiler | 300 | 20 |

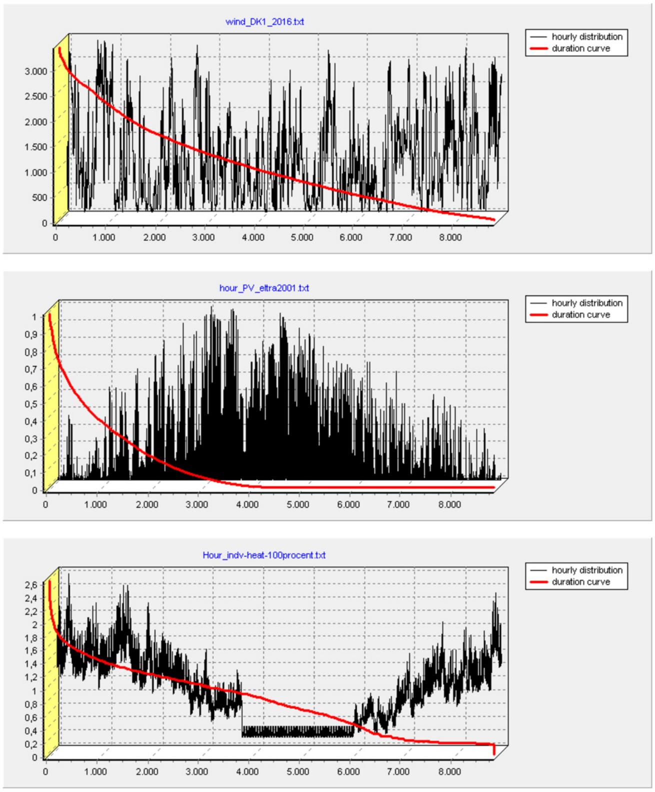

**Fig. 7.** Input data for hourly distribution of wind production, PV production and heat demand. Wind and PV productions represent actual historical variations. In the analysis, the Wind and PV productions are adjusted to expected future capacity factors using the methodology specified in Ref. [49].

To avoid the significant investment in electricity storage, one could choose to replace that option with thermal storage and central water based heating in buildings instead. Again, a total of 10 TWh is needed, but the cost would only be 250 billion EUR. However, a normal household with a heat demand of 15 MWh/year would require a water tank of 40–50 $m^3$ (300 times bigger than a normal hot water tank of 150 L), assuming a temperature difference of 60 °C. Additional, one still must account for the expansion of the electric grid.

To avoid the substantial investments in the electric grid, PV could be installed on rooftops in connection with thermal storage in individual buildings. Instead of 12,500 MW wind power capacity, this would require 39,000 MW PV capacity. However, due to the variable nature of solar power, it is necessary to match the hours of heat demand with the expected hours of PV energy production. Of the 47 TWh/year PV produced electricity, approx. 36 TWh/year will not match up with the hours of heat demand. In order to make a perfect hourly match, PV capacity must be increased even further to a total of 46,000 MW, and either individual electricity or thermal storage capacity totalling 27 TWh would be required. This amount of PV capacity would cost 35–40 billion EUR and the storage would cost either 8000 billion EUR for the electricity storage or 700 billion EUR for the thermal storage.

If savings are implemented and the heat demand is reduced to 28 instead of 47 TWh/year, the cost of supply would decrease substantially. In this case, the use of individual electric heating would require approx. 7400 MW wind power and increase the peak electricity load by 9000 MW, from 6000 MW to 15,000 MW. Of the 28 TWh/year wind produced electricity, approx. 8 TWh/year will not match up with the hours of heat demand. In order to make a perfect hourly match, an additional wind power capacity of 500 MW and an additional electricity storage capacity of approx. 4.5 TWh are needed. The total cost of wind turbines is approx. 15 billion EUR. The increase in electricity distribution grids would cost approx. 20 billion EUR and the total cost of electricity storage is 900 billion EUR.

The reductions in supply investment costs when considering heat savings (summing up to more than 1000 billion EUR when storage is included) are relatively high compared to the 30 billion EUR cost to implement the savings [32,33]. Similar conclusions can also be drawn for the variants with PV and thermal storage. Consequently, the inclusion of savings seems to be a very good idea in this alternative.

### 4.2. *Alternative 2: individual heat pumps ("smart grid")*

A more efficient alternative to electric heating is individual heat pumps. Here, it is assumed that heat pumps provide the base load in combination with electric boilers for peak load, with a resulting yearly average COP equal to 2.5 for the entire system. With this alternative, a heat demand of 47 TWh/year would need an electricity production of only 18.8 TWh/year. This solution will require approx. 5000 MW of additional wind power capacity to cover for the heating demand (additional to the electricity demand) and increase the peak electricity load by 11,000 MW, from 6000 MW to 17,000 MW. Out of 18.8 TWh/year, approx. 6 TWh/year wind power production will not match up with the hours of heat demand. In order to make a perfect hourly match, an increase in wind production of 1.4 TWh/year is needed, equal to a 400 MW increase in capacity, and electricity storage capacity must increase by almost 10,000 MW and approx. 3.7 TWh. Compared to Alternative 1, the costs for increased wind power capacity are reduced to 9 billion EUR, for the distribution grid they are approx. 20 billion EUR and 750 billion for the electricity storage.

Similar reductions in costs can be found for this alternative when using PV and individual thermal storage. However, as before, the necessary thermal storage size is still considerable, i.e. around 40–50 $m^3$ per household.

If savings are implemented and heat demand is reduced, this alternative is likely to have additional advantages, namely a reduction in operation temperatures for the heat pumps. Thus, in this variation it is assumed that the yearly average COP for the system is increased to 3, resulting in an electricity demand of only 9.3 TWh/year. The solution requires approx. 2500 MW of additional wind power and increases the peak electricity load by 6000 MW, from 6000 MW to 12,000 MW. Of the 9.3 TWh/year wind produce electricity, approx. 3 TWh/year will not match up with the hours of heat demand. In order to make a perfect hourly match, electricity storage capacity must increase by 5000 MW and approx. 2 TWh, and an increase in wind production of 0.7 TWh/year is needed to cover for storage losses (equal to an additional 200 MW wind power capacity). The costs are 5 billion EUR for the increased wind power capacity, approx. 10 billion EUR for the distribution grid and 400 billion EUR for the electricity storage.

If implemented with individual thermal storage, the storage need would be three times larger, i.e., 6 TWh. Still, the cost might be reduced to 150 billion EUR, but one would still have to find space for 20–30 $m^3$ storage tanks in each house. Also, this solution requires an increase in the heat pump capacity of around 20% in order to absorb the peaks in wind power production.

### 4.3. *Alternative 3: district heating and heat pumps as an integrated part of a renewable energy system ("smart energy systems")*

In this alternative, district heating is used to re-cycle low temperature waste heat from industry, thermal power production and biomass energy conversion. Additionally, further inclusion of waste incineration, geothermal energy and large-scale solar thermal is counted upon, as put forward in the IDA 2015 study [33]. In the IDA study, 66% of the heat demand is covered by district heating and 34% by individual heat pumps supplemented by solar thermal. Savings are implemented similar to the savings mentioned in the alternatives above. Individual houses are calculated as consuming 2.5 TWh of electricity for the heat pumps and an additional 2 TWh heat from solar thermal. District heating systems, including grid losses and some loss options of recycling waste heat due to seasonal reasons, are supplied by:

- 2.4 TWh solar thermal
- 19.7 TWh industrial waste heat (inclusive biomass conversion losses, electrolyses, etc.)
- 6.5 TWh CHP (Waste heat from thermal electricity production)
- 7.5 TWh heat from heat pumps, consuming 2.1 TWh of electricity
- 0.7 TWh biomass peak load boilers

Thermal storage capacity in the district heating systems is equal to 0.32 TWh plus 0.03 TWh seasonal heat storage for solar thermal. Storage capacity in individual heat pump systems is equal to 0.04 TWh.

To compare with the previous alternatives, a total electricity demand for heat pumps of 4.6 TWh/year requires approx. 1200 MW increased wind power capacity and an increase in peak electricity load of 1600 MW (max load of the heat pumps).

The cost of increased wind power capacity is 2 billion EUR and the storage cost is around 1.3 billion EUR. The need to expand the electricity grid is likely so small that it would not actually necessitate any practical expansion. However, other parts of the smart energy system such as electric vehicles may also add to the electricity demand. For this reason, and to compare with the previous alternatives, a cost for expanding the electricity distribution grid of 4 billion EUR is included.

However, this alternative has some additional costs. First, including the district heating grid will require an investment of a little more than 20 billion EUR. Then, the additional heat supply units listed above will cost a little more than 10 Billion EUR. In the Danish case, substantial parts of the district heating grid as well as the central water base heating systems in the houses are already present. However, to be able to compare and generalize to other possible cases, the full cost has been included.

### 4.4. Summary of results

The above results are summarized in Figs. 8 and 9. In addition to the costs mentioned above, costs for electric heating and central heating are added to account for the difference between some of the scenarios.

As explained in more detail in the previous sections, the costs represent expectations for future investment costs related to different technologies, some of which, by nature, are rough estimates. Especially with regard to grid infrastructures, the knowledge of specific costs is not well documented. However, as is clearly shown in the figures, the differences are so high that these uncertainties are not essential for the results and conclusions.

Moreover, the costs shown here are only for the investments. Similar diagrams can also be made for annual costs based on each technology's technical lifetime, an interest rate and the inclusion of O&M costs. However, since this would not really change the overall picture, only the investment costs are shown here. In any case, the lifetime is more or less the same for most of these technologies and O&M costs are small compared to the investments.

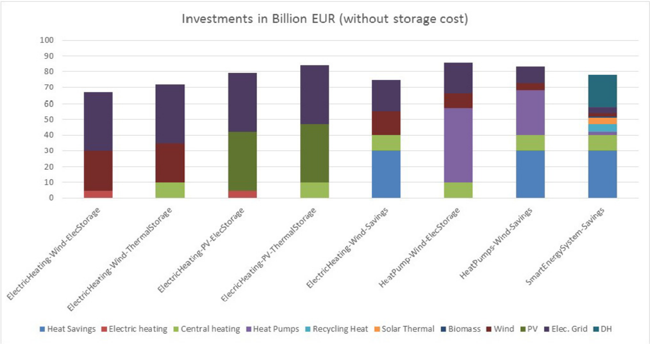

**Fig. 8.** Comparison of investment costs of the different alternatives, not including the storage costs.

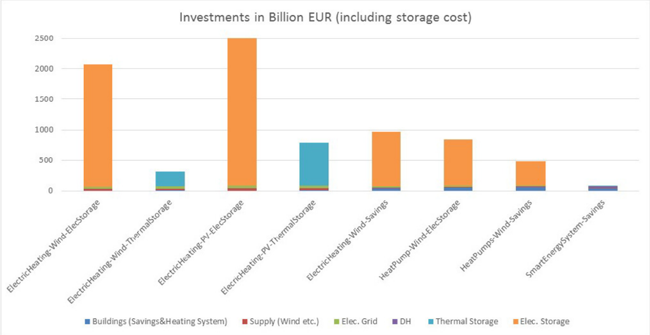

**Fig. 9.** Comparison of total investment costs of the different alternatives including storage costs. Note that not all costs of the alternative "ElectricHeating-PV-ElecStorage" can be seen in the diagram.

In Fig. 8, the total costs, excluding storage costs, are compared. As seen, the remaining costs of each scenario are in the same order of magnitude. In the Danish case, the district heating grid is already built. If this is taken into account, the "smart energy systems" alternative is the most affordable due to its high energy efficiency and recycling of low temperature waste heat. The second-best option is the electric heating and wind alternative, due to electric heating being more affordable than central heating and wind having lower costs than PV. In general, savings are not feasible, simply because producing electricity by wind and PV is cheaper. Moreover, heat pumps cannot compete with electric heating. In fig. 9, storage costs are included. As clearly shown, this completely changes the picture. Now, the "smart energy systems"alternative becomes even better by comparison, for the simple reason that the need for storage is smaller and the cost of large thermal storage capacities ismuch lower than electricity storage capacities.

## 5. Conclusions

In order to be concrete and to quantify realistic results, this study has used Denmark as a case. However, the principle results are general and will apply to many similar countries, even though Denmark differs from many other countries in two main aspects.

First, Denmark already has both a district heating and a natural gas grid, where many other countries have a higher share of natural gas and/or use more oil boilers for heating. However, this will not change the main outcome of the analysis, since the electricity distribution grid will be equally overloaded, no matter if the buildings used to be heated from district heating or natural gas.

Just, some countries should consider introducing or expanding district heating to achieve a suitable least-cost transformation to a future 100% renewable energy solution.

Second, Denmark is located to the North and has a higher heat demand than many Southern countries. However, in Europe the difference is not as significant as one would imagine. As shown in the Heat Roadmap Europe studies [2,61], the important factor when calculating the feasibility of district heating is the heat intensity, and since southern European countries have more dense urban areas the difference is not that big. However, some countries should also include cooling in a similar analysis.

Consequently, the following principle conclusions generally apply to most countries:

- The need for grid and storage infrastructures differ significantly between different scenarios. Therefore, it seems essential to include such consequences in the comparison of scenarios to achieve 100% renewable energy.
- In 100% renewable energy scenarios, the cost of grids and storage infrastructures may significantly exceed the cost of the renewable energy sources themselves, especially if one takes a sole-electricity approach.
- An integrated "Smart Energy Systems" approach with a focus on how the sub-sectors may complement and assist one another seems to be essential for the design and identification of suitable least cost solutions to transform a system into a 100% renewable energy system.
- Savings (in this paper, heat savings) have a significant influence on the need for grid and storage infrastructures. Thus, savings, which are not or only barely feasible compared to the production cost of renewable energy, may indeed be very feasible when grid and storage infrastructures are included in the analysis.
- Statements such as "no need to save if wind is becoming so cheap" and investment decisions based on current marginal prices leading to a strategy of expanding electric heating and no savings may lead us on a track that will not take us to 100% renewable energy solutions due to the extreme "hidden" costs regarding grid and storage infrastructures.

## Acknowledgement

The work presented in this article is a result of the research activities of the Strategic Research Centre for 4th Generation District Heating (4DH) and the RE-INVEST project "Renewable Energy Investment Strategies - A two-dimensional interconnectivity approach project" as well as the project "Innovative re-making of markets and business models in a renewable energy system based on wind power (I-REMB)". The work has received funding from the Danish research program ForskEL and Innovation Fund Denmark. Moreover, I wish to thank the audience for helpful questions and comments during the presentation of the results at the 12th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES) in Dubrovnik, Croatia in October 2017.

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