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The Role of Sustainable Buildings in 100 % Renewable Energy Systems

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ABSTRACT: This paper takes an overall energy system approach to the role of sustainable buildings in 100 per cent renewable energy systems based on the case of Denmark. In 2006, the Danish Government formulated the long-term objective of reaching a 100 per cent renewable energy system and a few months later the Danish Society of Engineers proposed how to do this by the year 2050. Based on such proposal among others, this paper highlights the role of sustainable buildings reaching the following three conclusions: First, energy demands in existing as well as new buildings have to be decreased. A suitable target seems to be to cut space heating demands by 50 per cent on average. Next, the remaining heat demand should be supplied by a combination of district heating in urban areas and individual heat pumps in the buildings outside urban areas. Finally, exchange of electricity from plus and net zero energy buildings can be both negative and positive for the system and should be dealt with at an integrated system level.

1. INTRODUCTION

In most countries, buildings account for a substantial part of the energy supply. Therefore, the development of sustainable buildings plays an important role in the transformation of national energy systems into future sustainable energy supplies aiming at reductions in fossil fuels and CO_2 emissions. The design and perspective of sustainable buildings have been analysed and described in many recent papers including concepts like net zero emission buildings and plus energy houses. However, such papers mostly deal with future buildings and do not include all the existing buildings which, due to the long lifetime of buildings, are expected to remain for many decades to come. Some papers have addressed how to reduce heat demands in existing buildings and have come to the conclusion that such effort involves a significant investment cost but results in important operational savings. However, the share of existing buildings is expected to remain high for many years. E.g., in Denmark, the share of such buildings is expected to be as high as 85-90 per cent in the year 2030. And no study has been found which identifies how to completely avoid heat demands in existing buildings at a reasonable cost and within a relevant time frame seen in the light of dealing with climate change (Lund, Möller, Mathiesen and Dyrelund 2010).

Importantly, it cannot be concluded from a purely house heating perspective how much should be invested in reducing energy demands compared to alternative investments in supplying the remaining heat, or whether one strategy with regard to heat supply fits better than the other into the implementation of future sustainable and renewable energy systems. One has to include the rest of the energy system in order to evaluate how to use the available resources in the overall system in the best way and how to combine energy savings and efficiency measures with renewable energy in order to meet the target to put an end to fossil fuels at the lowest possible cost for society.

This paper takes an overall energy system approach to the role of sustainable buildings in 100 per cent renewable energy systems based on the case of Denmark. In 2006, the Danish

Government formulated the long-term objective of transforming the Danish energy supply into being based solely on renewable energy and a few months later the Danish Society of Engineers (IDA) published an energy plan proposal advocating how to implement such target by the year 2050. Since then, a number of other proposals have been put forward including Heat Plan Denmark in 2008 and 2010 and the recent study of the Danish Commission on Climate Change Policy. Consensus seems to convey from all these studies with regard to the role of buildings including, among others, how much energy consumptions ought to be reduced and how the remaining demand for hot water and space heating should be supplied.

This paper seeks to identify and advance knowledge based on such studies to answer the following three key questions with regard to the development of sustainable energy buildings seen from an overall energy systems perspective: How much should heat demands be reduced in the buildings? How should the remaining heat demand be supplied? And how should exchange of electricity from net zero energy buildings be treated and dealt with?

2. HEAT DEMANDS IN SUSTAINABLE BUILDINGS

In his opening speech to the Danish Parliament in October 2006, the Danish Prime Minister announced the long-term target for Denmark: 100 per cent independency of fossil fuels and nuclear power. A few months later, the Danish Society of Engineers put forward a proposal on how and when to achieve such targets (Lund and Mathiesen, 2009). This proposal was the result of the "Energy Year 2006", in which 1600 participants during more than 40 seminars discussed and designed a model for the future energy system of Denmark, putting emphasis on energy efficiency, CO_2 reduction, and industrial development. The proposal was presented as the IDA Energy Plan 2030. Later in 2009, the plan was expanded to include the other sectors involving greenhouse gas emissions and published as the IDA Climate Plan 2050 (Mathiesen, Lund and Karlsson, 2010). Since then, several similar proposals have been made by various groups and organisations in Denmark including the recent study of the Danish Commission on Climate Change Policy. The following analysis refers to the IDA Energy Plan. However, it may as well refer to the other studies.

The design of 100 per cent renewable energy systems has to meet especially three major challenges. One challenge is to integrate a high share of intermittent resources into the energy system, especially the electricity supply. The other is to include the transportation sector in the strategies, and the third is to identify a proper combination of available resources including the involvement of biomass.

Consequently both the IDA Energy Plan and Climate Plan included detailed energy system analysis based on hour by hour computer simulations leading to the design of flexible energy systems with the ability to balance the electricity supply and demand and to exchange electricity production on the international electricity markets. The analysis was made by use of the Advanced Energy System Analysis model EnergyPLAN. For further description and documentation, please consult: www.EnergyPLAN.dk.

The results of the IDA Energy Plan were detailed system designs and energy balances for two energy target years: year 2050 with 100 per cent renewable energy from biomass and combinations of wind, wave and solar power; and year 2030 with 50 per cent renewable energy, emphasising the first important steps on the way. For the first step until 2030, the results include detailed socio-economic feasibility studies, electricity market trade calculations, and sensitivity analyses.

Three targets were formulated for the future Danish energy system in the year 2030:

- To maintain security of energy supply
- To cut CO_2 emissions by 50 per cent by 2030 compared to the 1990 level
- To create employment and to raise export in the energy industry by a factor 4

The target of maintaining security of supply refers to the fact that Denmark, at present, is a net exporter of energy due to the production of oil and natural gas in the North Sea. However, the reserves are expected to last for only a few more decades. Consequently, Denmark will soon either have to start importing energy or develop domestic renewable energy alternatives.

Based on such targets, the work was divided into 7 themes under which the following three types of seminars were held: First, a status and knowledge seminar; second, a future scenario seminar, and finally, a roadmap seminar. The process involved around 40 seminars with more than 1600 participants and resulted in a number of suggestions and proposals on how each theme could contribute to the national targets.

The contributions involved a long list of energy demand side management and efficiency measures within households, industry and transportation, together with a wide range of improved energy conversion technologies and renewable energy sources, putting emphasis on energy efficiency, CO_2 reduction, and industrial development. All such proposals were described in relation to a Danish 2030 "business as usual" reference. Such description involved technical consequences as well as investment and operation and maintenance costs.

After completing the process of comparison and discussion between experts and overall systems analysis, the proposals for the year 2030 ended up being a long list of measures including investments in energy savings and efficiency improvements as well as investments in renewable energy resources and technologies. One element was the reduction of space heating demands in buildings by 50 per cent. In order to achieve a 100 per cent renewable energy supply, a number of additional initiatives prolonging the 2030 energy system were proposed by including the further reduction of heat demands in buildings by another 20 per cent.

The socio-economic feasibility and the CO_2 emission of each proposal have been evaluated marginally in both the reference system and the alternative system. The process has led to the identification of proposals with predominantly positive feasibility. However, some proposals with negative feasibility have been included in the overall plan for other reasons. Some have good export potential. Some are important in order to be able to reach the final target of 100 per cent renewable energy in the next step. And others have important environmental benefits. The reduction of space heating demands by 50 per cent had a small positive feasibility for buildings outside district heating areas while the feasibility was slightly negative for buildings connected to district heating. However, it was concluded that since the difference was small, it would be too complicated to differentiate the implementation.

Looking at the other plans published afterwards, there seems to be consensus on the target of 50 per cent as a good balance between identifying a least cost solution when taking into consideration the sensitivity and risks involved with regard to fuel prices, energy security and environmental consequences.

3. HEAT SUPPLY OF SUSTAINABLE BUILDINGS

In 2008 (Lund, Möller, Mathiesen and Dyrelund, 2010), and repeated in 2010, Heat Plan Denmark conducted analyses on how sustainable buildings should be heated in future renewable energy systems. At present, the share of renewable energy in Denmark is almost 20 per cent. From such point of departure, Heat Plan Denmark defines a scenario framework similar to the proposal of the Danish Society of Engineers described above in which the Danish system is converted to 100 per cent renewable energy sources (RES) in the year 2060 including reductions in space heating demand by 75 per cent. By use of a detailed energy system analysis of the complete national energy system, the consequences in relation to fuel demand, CO_2 emissions and cost are calculated for various heating options, including district heating as well as individual heat pumps and micro CHPs (Combined Heat and Power). The study includes almost 25 per cent of the Danish building stock, namely those buildings which have individual gas or oil boilers today and could be substituted by district heating or a more efficient individual heat source.

The starting point of Heat Plan Denmark was the year 2006 in which 46 per cent of the Danish net heat demand (equal to 60 per cent of the households) is met by district heating mainly based on Combined Heat and Power production (CHP). The remaining part is mostly heated by individual boilers based on oil, natural gas or biomass. By use of advanced GIS models, the cost of connecting different parts of the remaining buildings has been identified. The identification has been made by combining a geographical model based on the Danish building register with a heat district model maintained by the Danish energy authorities. The specific models and applications are described further in (Möller and Lund, 2010).

Compared to the situation in 2006 as described above, three scenarios of potential expansion of district heating were defined and identified in which the share of district heating was expanded to as much as 70 per cent.

Compared to the present 2006 situation, the future energy systems include more wind power, heat savings and better CHP and power plants, etc. in which the Danish governmental vision of 100 per cent RES is reached by the year 2060 by implementing the following changes:

- Energy consumption from oil and natural gas production in the Danish North Sea is terminated.
- Fuel demand at CHP and power plants is converted to biogas and/or hydrogen.
- Fuel demand of boilers is converted to biomass such as straw and/or wood.
- The fuel demand of the industry is cut by 50 per cent and converted to biogas and/or biomass.
- Individual heating is converted to biomass boilers (in the reference scenario).
- Diesel for transport is replaced by bio petrol in the ratio 1:1.
- Petrol for transport is replaced by electricity in the ratio 3:1.

In such a 100 per cent RES vision, 66 TWh of biomass divided into 31 TWh biogas/syngas, 24 TWh bio petrol and 11 TWh solid biomass is needed in addition to wind power (27 TWh) and waste (15 TWh). However, in return, an excess electricity production of 5.6 TWh/year is created. Such excess production can be exported or it may be converted into hydrogen and thus reduce the demand for biogas by approx. 4 TWh. In the scenario, it has been chosen to add the capacity of electrolysers of 1000 MW resulting in a hydrogen production of 3.2 TWh/year and reducing the biomass demand to approx. 64 TWh. Including waste, the total demand for biomass resources adds up to 80 TWh/year, similar to 290 PJ/year. Such demand for biomass resources is within the magnitude of domestic Danish resources, which has been estimated at between 165 and 400 PJ/year, depending on the inclusion of energy crops (Lund and Mathiesen, 2009).

Heat Plan Denmark investigated how the buildings in question should be heated from the perspective of the overall system and came to the following conclusions:

Micro-CHP based on fuel cells on hydrogen does not seem to be able to reduce fuel demand, CO_2 emissions or cost, neither in the present system nor in a future 100 per cent renewable energy system. The efficiency is simply too low and the cost too high. Moreover, better and more cost-effective solutions can be found to deal with the problem of excess electricity production from wind power and CHP.

Micro-CHP based on natural gas seems to be an efficient way to reduce fuel demand and especially CO_2 emissions in the short term. CO_2 emissions are reduced both by expanding CHP and by converting from coal to natural gas in the overall system. The solution is, however, very expensive compared to district heating because of the substantial investments in micro CHP units in various buildings. In the long term perspective, in a 100 per cent renewable energy system, the solution is not competitive with regard to fuel, CO_2 emission and cost reduction compared to district heating and not even compared to individual boilers based on biomass.

With the high oil and gas prices of 2008 and, at the same time, low coal and Nord Pool electricity prices, electric heating is a socio-economically reasonable alternative mainly because of the saved central heating system cost. In the short term, this is not valid for houses which already have central heating. And in the long-term perspective, electric heating is bad for fuel demand and CO_2 emissions. Moreover, this alternative becomes very sensitive to potential increases in future fuel demand.

Individual heat pumps seem to be the best alternative to district heating. In the short term, heat pumps are to be found at the same level as district heating in terms of fuel efficiency, CO_2 emissions and cost. The cost is a little higher close to the district heating system but a little lower in houses further away. In the long-term perspective, in a 100 per cent renewable energy system, the fuel efficiency is high and, with regard to cost, the solution is more or less equal to district heating. However, it is highly dependent on the distance to existing district heating grids.

In an overall perspective, the conclusion seems to be that the best solution will be to combine a gradual expansion of district heating with individual heat pumps in the rest of the areas. It must, however, be emphasised that the analysis is based on a gradual improvement of district heating technologies, implementing among other initiatives a decrease in temperature in combination with a reduction in space heating demand including a reduction in the consumers' return temperature. Therefore, it is crucial to continue the present development in such a direction. Moreover, the expansion of district heating will help utilise heat production from waste incineration and industrial excess heat production which has been included in the analysis.

4. EXCHANGE OF ELECTRICITY FROM NZEB BUILDINGS (MISMATCH)

As described above, there seems to be consensus on heading for a target of an average reduction in space heating demand of approx. 50 per cent. However, the 50 per cent is the average among both existing and new buildings in which the least cost solution will be to have even lower heat demand in new buildings. Moreover, buildings may benefit from adding on-site renewable technologies such as solar thermal and photovoltaics resulting in plus or net zero energy buildings, which involves the issue of electricity exchange known as the mismatch problem. The mismatch arises from hourly differences in energy production and consumption at the building level and results in the need for exchange of electricity via the public grid even though the building has an annual net-exchange of zero. Again, one has to take an overall energy system approach to analysing such problem in a proper way. Such approach has been taken in the paper (Lund, Marszal and Heiselberg, 2010) in which it is emphasised that, from the viewpoint of the overall system, the mismatch problem should not be dealt with at the individual level. It should be compensated for at the aggregated level for the following reasons:

Firstly, the cost of investing and operating one big battery of 10,000 kWh is substantially lower than operating a thousand 10 kWh batteries, among others, because large batteries make it possible to utilise new battery technology like vanadium redox flow batteries. Moreover, other options exist at the system level which can provide the same regulation at even lower costs. Such options are: Changing the regulation of existing small CHP plants; introducing large-scale heat pumps at existing CHP and district heating supplies; using electricity in the transport sector; or introducing electricity storage systems such as e.g. CAES (Lund, 2010). Consequently, one will save money dealing with these problems at the aggregated level.

Secondly, the mismatch of the individual building is levelled out at the aggregated level. One may compare it to the design of power supply systems. Power plants are not designed to meet the needs of the number of consumers multiplied by the maximum consumption of each consumer. In such case, one would make huge over-investments in transmission lines and power stations. Such maximum consumption never happens for the simple reason that not all consumers peak in consumption at the same time. At the aggregated level, things are levelled out. The same concerns mismatches created by changes in electricity demand and photovoltaic or wind power production at the individual building level. The mismatch of one building is partly compensated for by mismatches of other buildings and trying to compensate for each mismatch inside each building will lead to situations in which one building is charging a battery at the same time as another building is discharging a battery, only leading to unnecessary losses. Seen from the viewpoint of the electricity supply system, it is not the individual “one building mismatch” that is interesting; it is the sum of mismatches from all buildings that counts. One would make significant over-investments and inefficient operation of the system if one tried to compensate for each mismatch at the individual level compared to the aggregated level.

Thirdly, one risks making things worse. The reason is that a mismatch, from the individual building point of view, per definition is looked upon in a negative light. If there is a mismatch, it is defined as a problem that has to be solved. However, from the viewpoint of the electricity supply system a mismatch is not necessarily negative, it may also be positive. The reason is that typical electricity consumption is high during the day and low during nights and weekends. Such variation is typical for all countries even though the specific shape of the curve differs from the electricity demand of one country to another. From the electricity supply point of view, a mismatch that decreases demand during the night and increases it during the day is negative. Such mismatch will increase the demand for capacity and increase production of expensive units during peak hours and only save less expensive units during base load hours. However, for the same reason, a mismatch resulting in the opposite, i.e. a decrease during peak load and an increase during base load, creates a positive change for the system. Consequently, such mismatch should not be compensated for, and if one invests in flexible demand or storage systems at the building level to minimise such mismatch, one will only make things worse.

For these three reasons, mismatches should be dealt with at the aggregated level and not at the individual building level. Instead, the paper (Lund, Marszal and Heiselberg, 2010) suggests to compensate for the mismatch of one building by increasing (or decreasing) the capacity of the energy production unit.

The size of the mismatch factor is a function of two elements: On the one hand, the character of the mismatch of the building, i.e. if the production unit is based on e.g. photovoltaics or wind, and on the other hand, the system in which the mismatch should be compensated for.

Based on historical data for the western Danish electricity supply area, the paper (Lund, Marszal and Heiselberg, 2010) makes a first attempt to quantify mismatch compensation factors for buildings with photovoltaic collectors or small on-site wind turbines. For such analysis, the paper has defined four types of ZEBs: Two with only electricity demand and photovoltaic or wind production and two with both heat and electricity demand with solar thermal production, heat storage and heat pumps in combination with either photovoltaics or wind. The four types of NZEBs have been analysed during a period of ten years using aggregated data for the western Danish electricity supply area, being part of the Nord Pool electricity market. Mismatch compensation factors have been calculated for each year and each type of NZEB.

For the wind ZEBs, it has been possible to calculate the mismatch compensation factor for all 10 years using the exact distribution of aggregated wind production of each year. This is considered important in the Danish system since the wind power share is high enough to influence the price, while e.g. photovoltaics have such a small share that there is practically no influence on the electricity price.

The results indicate that such compensation factors in general are a little below one for photovoltaics and a little above one for wind turbines. Consequently, the mismatch is not a huge problem for the system even though it is substantial when calculated for each individual building. Moreover, the mismatch compensation factor does not seem to vary much between NZEBs with only electricity demand and NZEBs with both heat and electricity demand.

Based on the analysis in this paper, it is proposed to use a mismatch compensation factor of 0.9 for NZEBs with photovoltaics and a factor of 1.1 for NZEBs with wind power. Such factors should be regarded a first attempt. It should be emphasised that these factors have been calculated on the basis of economical market prices and not on the basis of energy consumption or CO_2 emissions. The marginal market value represents the differences in marginal production costs which reflect the fuel consumption and thus the CO_2 emission. However, it is not accurate with regard to energy consumption and CO_2 emission. Consequently, it is recommended to make further investigations using numbers on energy consumption and emissions instead of market prices.

The general conclusion that photovoltaics create a positive mismatch while wind creates a negative mismatch and that none of these are a huge problem from the viewpoint of the overall electricity supply is expected to last if making calculations based on energy and emissions. However, the specific value of the mismatch compensation factor may differ slightly.

The mismatch compensation factor relates to the operation of the building and does not include any life-cycle considerations with regard to the embodied energy of the building. However, there is no reason why such consideration could not be combined by adjusting the energy production units so that they compensate for the mismatch as well as the embodied energy.

5. SUMMARY AND CONCLUSION

This paper has taken an overall energy system approach to the role of sustainable buildings in 100 per cent renewable energy systems based on the case of Denmark. Based on the design and analysis of proposals for future 100 per cent renewable energy systems, this paper has highlighted the role of sustainable buildings and emphasised the following three topics:

First, energy demand in both existing and new buildings has to be decreased compared to the present level. All recent plans and proposals for how and when to reach political goals of transforming the existing fossil fuel-based energy system into a 100 per cent renewable energy system or similar include energy conservation in buildings as an important element. A suitable target seems to be to cut space heating demand by 50 per cent on average during 2030-2050.

Second, the remaining heat demand should be supplied by a combination of district heating in urban areas and individual heat pumps in the buildings outside urban areas. In an overall perspective, the best solution will be to combine a gradual expansion of district heating with individual heat pumps in the rest of the areas. Individual heat pumps seem to be the best alternative to district heating. In the long-term perspective, in a 100 per cent renewable energy system fuel efficiency is high and, with regard to cost, the solution is more or less equal to district heating. However, it is highly dependent on the distance to existing district heating grids.

Finally, exchange of electricity from plus and net zero energy buildings can be both negative and positive for the system and should be dealt with at an integrated system level. Moreover, there are often both an element of levelling out mismatches between individual buildings and an element of economy of scale. For these three reasons, mismatches should be dealt with at the aggregated level and not at the individual building level. Instead, it is suggested to compensate for the mismatch of one building by increasing (or decreasing) the capacity of the energy production unit. The general conclusion that photovoltaics create a positive mismatch while wind creates a negative mismatch and that none of these are a huge problem from the viewpoint of the overall electricity supply is expected to last if making calculations based on energy and emissions. However, the specific value of the mismatch compensation factor may differ slightly.

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