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Heat saving strategies in sustainable smart energy systems

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ABSTRACT

This paper investigates to which extent heat should be saved rather than produced and to which extent district heating infrastructures, rather than individual heating solutions, should be used in future sustainable smart energy systems. Based on a concrete proposal to implement the Danish governmental 2050 fossil-free vision, this paper identifies marginal heat production costs and compares these to marginal heat savings costs for two different levels of district heating. A suitable least-cost heating strategy seems to be to invest in an approximately 50% decrease in net heat demands in new buildings and buildings that are being renovated anyway, while the implementation of heat savings in buildings that are not being renovated hardly pays. Moreover, the analysis points in the direction that a least-cost strategy will be to provide approximately 2/3 of the heat demand from district heating and the rest from individual heat pumps.

Keywords:

Energy Efficiency,
Renewable energy,
Heating strategy,
Heat savings,
District heating,
Smart energy

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1. Introduction and overall methodology

The design of future sustainable energy solutions including 100 per cent renewable systems is described in a number of recent reports and studies including [1–7]. Such systems are typically based on a combination of renewable energy sources (RES) such as wind, geothermal and solar, together with residual resources such as waste and biomass. In order to ease the pressure on biomass resources and investments in renewable energy in future sustainable energy systems, feasible solutions typically involve a substantial focus on energy conservation and energy efficiency measures. One of the important issues to address is, in some countries, the heating and, in others, the cooling of buildings. Thus, the issue of reducing heat demands through the implementation of low-energy buildings and how to heat these buildings becomes essential.

Different methodologies have been used to address this question for different countries around the world. One example is thermo-economic analysis with a focus on the relation between capital costs and thermodynamic losses, which has been applied to, e.g., Turkey [8]. Another example is bioclimatic architecture, which has been applied to the Hellenic building sector [9]. A third example is energy retrofit simulation, which has been applied to Italy [10]. The latter also emphasizes the relation between the energy performance of a building and its value on the real estate market [11].

The design and perspective of low-energy buildings have been analysed and described in many recent papers [12,13], including concepts like energy efficient buildings [14,15], zero emission buildings, and plus energy houses [16–18]. However, these papers mostly deal with future buildings and not as often the existing building stock which, due to the long lifetime of buildings, is expected to constitute the major part of the heat demand for many decades to come. Some papers address the reduction of heat demands in existing

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buildings and conclude that such an effort involves a significant investment cost [19, 20]. Consequently, an important question is to which extent least-cost heating strategies should involve such an investment.

Another essential question for heating strategies is how to provide the remaining heat. For example, how much should one invest in infrastructures such as district heating? District heating comprises a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralised plants or a number of distributed heat producing units. This approach allows the use of any available source of heat. The inclusion of district heating in future sustainable cities allows the wide use of combined heat and power (CHP) together with the utilisation of heat from waste-to-energy and various industrial surplus heat sources as well as the use of geothermal and solar thermal heat [21–27]. In the future, such industrial processes may involve various processes of converting solid biomass fractions into bio(syn)gas and/or different sorts of liquid biofuels for transport purposes, among others [28, 29].

To complicate matters even more, heating strategies should, however, not be designed for the present energy system but for the future system. Further, one of the future challenges will be to integrate heating and cooling with the electricity sector as well as the transport sector [30–32]. In [33–35], such a future system is referred to as a *smart energy system*, i.e., an energy system in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them and to achieve an optimal solution for each individual sector as well as for the overall energy system. A transition from the current fossil fuel- and nuclear-based energy systems into future sustainable energy systems requires the large-scale integration of an increasing level of intermittent renewable energy. This also entails the rethinking and redesign of the energy system. In smart energy systems, focus is on the integration of the electricity, heating, cooling, and transport sectors, and on using the flexibility in demands and various short-term and longer term storage options across the different sectors. To enable this, the smart energy system must coordinate a number of smart grid infrastructures for the different sectors in the energy system, which includes electricity grids, district heating and cooling grids, gas grids, and different fuel infrastructures.

A number of recent studies [36–48], including Heat Roadmap Europe [36, 43], come to the conclusion that district heating plays an important role in the implementation of future sustainable energy systems. However, the same reports also emphasise that the present district heating system must undergo a radical change into low-temperature district heating networks to interact with low-energy buildings and become an integrated part of smart energy systems.

The aim of this paper is to present a methodology to identify least-cost strategies of reductions in the heat demand of buildings as a part of implementing sustainable smart energy systems. The basic assumption is that these reductions have an important impact but are also very investment intensive. The important point which is emphasised in this paper is that the size of the investment costs strongly depends on whether energy conservation is done in existing buildings or as additional investments in new buildings. And it depends on whether investments are made solely for the purpose of reducing heat demand or as an integrated part of renovation which will take place anyway. Moreover, the identification of proper strategies depends on the marginal alternative production of the energy system, and the cost of this marginal production again depends on which system one addresses. In the following, the context used is the case of Denmark, in which the Government has formulated a strategy for transforming the whole energy system into a system based on 100% renewable energy by year 2050.

The purpose of this paper is to analyse and answer the following three questions:

1. To which extent should heat for space heating and hot water be reduced by saving measures and investments and to which extent should it be produced/supplied?
2. Which is the best combination of investments in heat savings, divided into new houses and existing houses?
3. Which share of the supply should come from district heating and which share from individual solutions?

2. Marginal production cost in a future sustainable smart energy system

2.1. Definition of future sustainable smart energy system

The identification of a least-cost heating strategy highly depends on the context; i.e., on the one hand, which kind of sustainable energy system one expects to have, and on the other hand, how one expects the building sector to develop.

Here, the analyses have been carried out in the context of the decision of the Danish Government to transform the Danish energy supply to be fossil-free by 2050. A specific proposal on how to implement this goal has been defined in a research project financed by the Danish Council for Strategic Research in 2011 (CEESA) [49], which again is based on a proposal put forward by the Danish Society of Engineers (IDA) in 2006 [49] and 2009 [39]. The IDA study is based on the technical inputs of the members and is the result of the organization's "Energy Year 2006," during which 1600 participants at more than 40 seminars discussed and designed a model for the future energy system of Denmark. The CEESA scenario is the result of the collaboration of researchers from five Danish universities, performing a coherent energy and environmental systems analysis (CEESA) of the transformation into 100 per cent renewable energy systems. The study might be seen as a follow-up on the first IDA Plan, in which an important further step was taken with regard to the *smart energy systems* analysis and the integration of the transport fuel pathways. Among others, hour-by-hour analyses of electricity and district heating are supplemented with similar hour-by-hour calculations for gas. Both the IDA and CEESA scenarios involve the design of coherent and complex renewable energy systems, including the suitable integration of energy conversion and storage technologies. Furthermore, both studies are based on detailed hour-by-hour simulations carried out in the EnergyPLAN software.

The CEESA study is an example of the design of a 100% Renewable Energy System based on the principles outlined in the paper "Renewable Energy Strategies for Sustainable Development"[7]. This involves a combination of 1) energy savings in consumption such as investments in better buildings and appliances, 2) energy efficiency measures in production such as the expansion of CHP and better efficiencies, and 3) the replacement of fossil fuels by renewable energy. The main assumption is that a fossil fuel-based supply is replaced by a renewable system through investments in energy efficiency and renewable energy sources.

In CEESA, energy savings and direct electricity consumption are given high priority, and all scenarios rely on a holistic *smart energy system* approach as explained in [33]. This includes the use of heat storages, district heating with CHP plants, and large heat pumps as well as the integration of transport fuel pathways with the use of gas storage. These *smart energy systems* enable a flexible and efficient integration of large amounts of fluctuating electricity production from wind turbines and photovoltaics. The gas grids and liquid fuels allow long-term storage, while the electric vehicles and heat pumps provide shorter-term storage and flexibility.

The CEESA project includes a careful examination of the pathways to provide biomass resources. The starting point is an overview of the available amount of residual resources in terms of straw, wood, and biogas from manure, etc., summing up to approximately 180 PJ/year. A shift in forest management practices and cereal cultivars could increase the potential further to approximately 240 PJ/year by 2050. The 180 PJ/year could also be increased to 200 PJ by enacting dietary changes. This potential represents the use of residual resources only. This means that the CEESA 2050 scenario is kept within the boundaries of residual resources. It should be noted that a target of 240 PJ/year by 2050 implies a number of potential conflicts due to many different demands and expectations from ecosystem services; it requires the conversion of agricultural land otherwise allocated to food crop production to energy crop production, potentially reducing food and feed production. All crop residues must be harvested, potentially reducing the carbon pool in soils. A way to reduce these potential conflicts is to reduce the demand for biomass for energy or to further develop agriculture and forestry to increase the biomass production per unit of land.

One important learning outcome from the hourly analysis of the complete system including both electricity and gas balances is that relatively cheap gas storage capacities (which in the Danish case are already there) can be used to balance the integration of wind power into the electricity grid. Consequently, in the CEESA 2050 scenario, it is possible to decrease excess electricity production to nearly zero at the same time as high fuel efficiencies are achieved by using heat and gas storages rather than electricity storages.

Both the IDA and the CEESA scenarios are comprehensive in the way that they provide a 100% renewable solution to the complete system, i.e., including all transport also ships and aeroplanes. Moreover, as already explained, they have a focus on identifying the best solution for the whole system while taking into consideration all kinds of synergies between the individual sectors, i.e., taking a smart energy systems approach.

2.2. Methodology, software and assumptions

To identify the marginal cost of heat production, this study has applied the same software and model as in the IDA and CEESA scenarios. The EnergyPLAN software makes hourly calculations of the complete smart energy system as described above for countries like Denmark. For other countries, the model can also include the integration with district cooling and desalination [50]. The model is publicly available and further described on www.EnergyPLAN.eu.

CEESA has been evaluated on the basis of the fuel prices shown in Table 1.

In this study, the important assumption is the natural gas price of 10.4 EUR/GJ, since it illustrates the cost of changes between the scenarios in the use of less or more synthetic gas similar to natural gas. In CEESA, the low price scenario is based on assumptions from the Danish Energy Agency in 2008; medium fuel prices from 2011, and high fuel costs for fossil fuels are based on actual prices in the summer of 2008. To form a high biomass fuel cost level, twice the biomass price difference assumed by the Danish Energy Agency from 2008 and 2010 is added to the medium biomass prices. The high fuel cost level is constructed for biomass and stated in *italics*.

With regard to buildings, the CEESA scenario includes an expansion of heated areas of approximately 40% by 2050 and a cut in the space heating demand per unit of 50%. Moreover, the scenario includes an expansion of the district heating share from the current level of approx. 50% to 66% in 2050. In this study, the CEESA scenario has been used to determine the marginal cost of changing the heat demand as well as the share of district heating in the following way. A matrix has been designed for the investigation consisting of the two different levels of district heating share and four different levels of annual heat demand reductions in the buildings, i.e. 25%, 50%, 75% and 100% of current space heating demand per unit.

In CEESA, the reference start heat demand was from 2008, while in this study, it has been adjusted to the statistics of 2010. According to these statistics, the net heat demand (space heating and hot water) in 2010 (after climate corrections) was a total of 50 TWh/year divided into 94.6 TJ/year (equal to 26.28 TWh/year) of district heating and 85.4 TJ/year (equal to 23.72 TWh/year) of individual heating. Thus, the share of district heating was 52.5%. With a 40% increase and no savings, the heat demand increases to 70 TWh in 2050.

Table 2 shows the development in the heated area in Denmark for the past 40 years and four 10-year growth rates have been identified. As can be seen, growth rates have a tendency to fall and have for the past 30 years been in the order of magnitude of 10%. In this study, an increase of the heated area is assumed equal to a 40 per cent increase by 2050 compared with 2010. Table 2 also shows the development in specific heat demands illustrating a decrease from 147 kWh/m^2 in 1970 to 122 kWh/m^2 in 2010 equal to a 17% decrease over a 40-year period. This historical development emphasizes the fact that the implementation of, e.g., a 50% decrease during the next 40 years will require an active policy [51].

Moreover, in the present situation, 15% of the heat demand is assumed to be hot water and 85% is for space heating. Based on these assumptions, the heat demands of the matrix have been calculated and divided into district and individual heating.

In the hourly modelling of the CEESA scenarios, the current hourly duration of heat demand and grid losses

Table 1: Fuel price assumptions in the CEESA scenario which have also been applied to this study. All prices are real prices expressed in 2010 value.

CEESA EUR/GJ (2010 costs)	Crude oil	Coal	Natural gas	Fuel oil	Diesel fuel/Gas oil	Petrol/JP	Straw / Wood chips	Wood pellets (general)	Energy crops
Low fuel costs	9.3	2.1	5.8	6.5	11.6	12.4	4.3	9.6	5.4
Medium fuel costs	15.0	3.3	10.4	13.6	17.0	17.6	5.6	11.1	7.5
High fuel costs (Real	21.2	5.6	14.7	19.2	23.7	21.2	*8.3*	*13.6*	*11.7*

Table 2: Historical development in the main parts of the Danish building stock. Based on the heat atlas described in [53].

Year (primo)	1970	1980	1990	2000	2010
Total heated area (Million m^2)	185.1	246.7	278.0	298.3	331.7
Total heat demand (TWh/year)	27163	34155	36793	38466	40327
Specific demand (kWh/m^2)	147	138	132	129	122
10-year growth factor		1.33	1.13	1.07	1.11

as well as the cost of expanding the district heating grid have been adjusted on the basis of the detailed study "Varmeplan Danmark (2008) [41, 53, 54]. The same source has been used to determine the cost of individual heat pumps for the areas outside district heating.

The investment cost of expanding the district heating grid from 46% in 2006 to 63% has in [54] been identified as 4.4 billion EUR. Here, it is considered to expand from 52% to 66%, which is a little less. On the other hand, the expansion concerns a higher level which increases the marginal costs. Consequently, it seems fair to use the same investment cost as an appropriate approximation. In the same source [53], it is discussed in detail how to benefit from heat savings either by reducing the capacity of the grid and/or reducing district heating temperatures and thereby the grid loss. This study assumes a reduction in temperatures and, as a consequence, the grid costs have not been changed for different levels of heat savings; only according to the different amounts of houses connected to the grid. In the calculations, a lifetime of 40 years and annual operation and maintenance costs of 1% of the investment are used.

Then, based on the CEESA scenario as explained above and using the EnergyPLAN model, the total annual costs of the different scenarios in the matrix have been calculated. The following changes in input between the scenarios have been made in the modelling:

- Heat demands and shares of district heating are as specified above
- The COPs of individual heat pumps depend on the heat demand and vary between 2.8 and 3.2 on average for both space heating and hot water.
- In Scenario B compared to Scenario A, a cost of 4.4 billion EUR is added for the extra district heating grid
- The capacity of district heating boilers is calculated as the maximum district heating demand plus 10 per cent
- The use of biomass is fixed so that any change in fuel demands becomes import/export of synthetic gas (except from scenario 25% in which some biomass is also saved).
- Power plant capacities are adjusted compared to the CEESA scenario to compensate any changes in individual heat pump electricity peak demands plus 20% reserve.

As described above, the CEESA scenario has been designed as a 100% renewable energy scenario using only available residual biomass resources. When changing the heat demand, the need for biomass and other renewable sources will consequently either increase or decrease. Here, the changes have been calculated in terms of changes in the need for net import/export of fuel equivalent to natural gas or similar gasses made on biogas/biomass. Since this is an economic assessment, the important aspect here is the price which has been set to 10.4 EUR/GJ as previously mentioned. More details can be found in [55], Appendix 1.

2.3. Results

The resulting annual costs of the different scenarios are shown in Figures 1 and 2. Basically (as illustrated in Figure 1), reductions in heat demands decrease the total costs of the complete energy supply. However (as illustrated in Figure 2), the marginal benefits of one unit of saved energy are reduced as more savings are implemented. This has to do with the low-temperature waste heat available in the system from industrial surplus, CHP (thermal or fuel cell power production), and biomass conversion processes. These resources are relatively low-cost resources and once they have been used, any additional heat demand gradually requires increased heat pump and/or boiler productions as well as additional investments in production capacity. Moreover, solar thermal and geothermal can better be exploited with an hourly distribution of a low energy demand than a high energy demand due to the seasonal differences being more severe with a high heat demand.

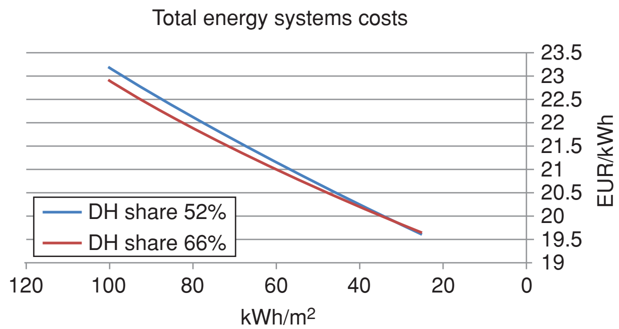

Figure 1: Total annual cost of different energy solutions in Denmark 2050 as a function of the percentage of heat savings per unit. 100% is equal to the current level of 122 kWh/m^2.

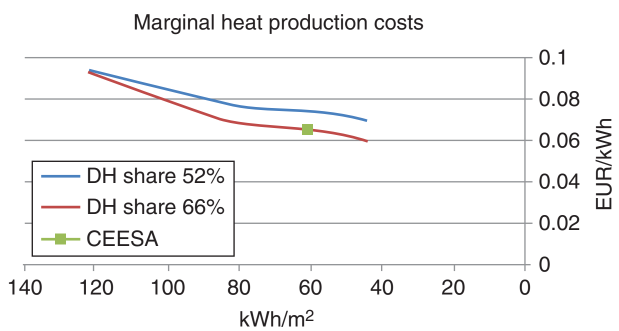

Figure 2: Marginal heat production cost as a function of specific heat demand.

In summary, the results in terms of changes in the total costs are as illustrated in Figure 1.

The total cost has been converted to marginal cost per unit as illustrated in Figure 2 under the assumption that the 2010 level corresponds to 122 kWh/m2 as listed in Table 2. Marginal costs are here found as the change in total cost related to the change in heat demand. In the conversion, it has been considered that hot water in the current level accounts for 15% equal to approx. 18 kWh/m2. This level has been kept constant.

Figure 2 illustrates the fact that the marginal heat production cost per unit of the overall energy system decreases from approx. 0.1 EUR/kWh to approx. 0.07 EUR/kWh with decreasing heat demands. Moreover, Figure 1 illustrates how an expansion of district heating will decrease the total (and per unit) costs as long as the average heat demand is above a level of 30% of the current specific heat demand.

The CEESA scenario of 66% district heating and a 50% cut in heat demands is marked in Figure 2.

3. Marginal saving cost

The next step has been to identify the marginal cost curve when increasing the energy saving activities for new and existing buildings, respectively. For new buildings, the marginal cost represents an increased investment in all new buildings, since the least-cost solution is to be found when all new buildings are insulated to the same level. However, for existing buildings, this is not the case, because the investment in conservation is mainly relevant in the cases in which renovation is being carried out anyway. Therefore, the least-cost solution (within a certain number of years, i.e. till 2050) is identified as a scenario in which the buildings being renovated include all energy conservation measures, while the buildings not being renovated are left more or less as they are. Consequently, for existing buildings, the marginal cost has been identified in such a way that it represents investments in an increasing number of buildings.

3.1. New buildings

When increasing the energy saving activities in new buildings, a marginal cost curve has been made based on the report "Cost-optimal levels of minimum energy performance requirements in the Danish building regulations" [56, 57] and data related to the study described in the report; see [55], Appendix 2. The report identifies the costs of different levels of energy savings in new single-family houses of 150 m^2. By creating a marginal cost curve from this data and combining it with the supply costs of energy from the previous section, an optimal level of savings can be identified. Not all future buildings will be single-family houses. However, due to time and data restrictions, this study is limited to this type.

When calculating such a marginal cost curve, one issue turned out to be very important: how to treat the marginal cost of mechanical ventilation? The above-mentioned report indicates that, at a certain point of increasing saving measures, mechanical ventilation must be installed in buildings to reach lower heat reductions than what is possible with natural ventilation. This creates two problems.

The first problem is that a change from natural to mechanical ventilation leads to an increase in the electricity demand due to the operation of the ventilation system. In principle, this electricity demand should be treated as a change to the smart energy system. However, for practical reasons and since this paper defines least-cost solutions, the electricity demand has been treated as a cost of 0.13 EUR/kWh. In principle, this cost reflects the marginal cost of producing one more unit of electricity in the smart energy system. However, due to the size of the electricity demand the exact value of this price is not essential.

The second problem is connected to the identification of the investment and operation costs of adding mechanical ventilation. This issue is discussed further in [55]. Based on this discussion, the following assessment is based on the assumption that mechanical ventilation is implemented independently from energy measures, since most new buildings require mechanical ventilation to maintain a certain level of indoor climate. In Figure 3, the marginal cost of decreasing the heat demand in new buildings is shown alongside the production curves from the previous section. As can be seen, investments in heat reductions are feasible up to a level of approx. 57 kWh/m^2. Hereafter, the marginal costs of heat supply will be lower.

3.2. Existing buildings

The second part of increasing the energy performance of buildings involves the refurbishment of the existing building stock. When determining the marginal cost curve for current buildings, the renovation of each building is assumed to take the building from the current energy use level to the most cost-efficient low energy use level. This means no "step-by-step" improvement, as was the case of the new buildings. The analysis includes two scenarios. One that shows the costs of improving the buildings under the assumption that they were to be refurbished anyway (marginal costs), and one that shows the total costs including the expenses related to initializing the refurbishment. This means that existing houses being refurbished anyway only include the costs of materials and marginal labour force in the same way as is the case of new houses. The numbers come from studies relating to the report "Heat Demand in Danish Buildings in 2050" [58]. The previous section analysed only one type of building, but here multiple types of buildings with different construction years are included.

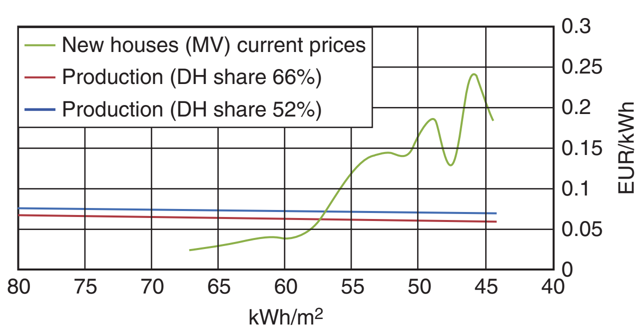

Figure 3: Marginal cost of improving the energy efficiency in a new house compared with marginal costs of heat supply. The marginal cost of heat savings is represented by new single-family houses in which the price of mechanical ventilation (MV) is not included.

Combining the different building types and the construction period involves 27 different categories, which to a certain extent show the variation in the Danish building stock. It is important to include this variation within the building stock because each category is different in terms of specific heat demand as well as the savings potential. However, the data does not include apartment blocks and office buildings since the numbers for these indicate too large efficiency increases. This means that the analysis only looks at the building types that would be the most expensive to refurbish; thus, for the total building mass, more buildings are most likely feasible to renovate.

The potential energy savings in newer buildings are not as high as in the older buildings and the costs of implementing the savings also differ. This means that for some building categories, higher heat savings can be achieved by implementing less expensive measures than in other building types. For each building category, five heat saving measures are implemented; these are roof, floor, outer wall, window, and ventilation. Based on data shown in [55] Appendix 2, it is possible to identify the costs of renovating each house.

The marginal cost and total cost are plotted on the y-axis, with the corresponding x coordinate being the average between the former building type and the latter building type. The points therefore illustrate an increase in the buildings renovated. The plot looks as shown in Figure 4.

4. Results and discussion

Figure 5 shows the combination of the previous analyses and calculations.

The following can be learned from the diagram:

- The least-cost heating strategy seems to be found with 35% to 53% savings; i.e., when the average heat demand per unit is decreased to

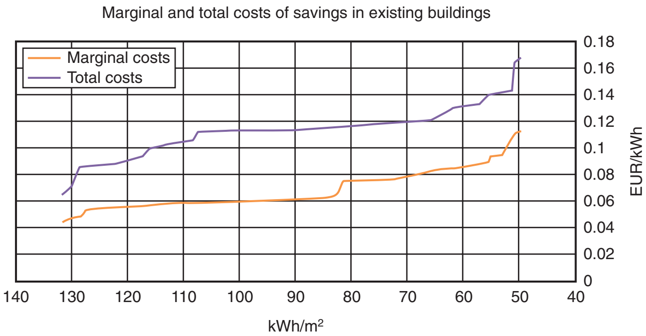

Figure 4: The marginal and total costs of energy renovating existing buildings represented here as single-family houses, farmhouses and terrace houses.

35–53% of the current level, equal to a decrease in the net heat demand per unit from the current 122 kWh/m^2 to approx. 58–80 kWh/m^2. However, because the graph only takes into account the single-family houses, farmhouses and terrace houses, and more cost-efficient savings are expected in apartment blocks and offices, the least-cost strategy is expected to be closer to 50% than 35%.

- Savings should primarily be implemented in new buildings and only in existing buildings in combination with renovation being carried out anyway. Otherwise the marginal costs are substantially higher than the heat production costs.

Moreover, based on the total cost shown in Figure 5, a least-cost heating strategy points in the direction of increasing the district heating share to approx. 2/3 rather than maintaining the current share.

The results of the analysis highlight the importance of identifying long-term heating strategies since the identified least-cost solution can best be implemented with a long time horizon. Thus, savings should mostly be implemented when renovations are being carried out anyway and a suitable district heating infrastructure should be developed over a long period.

As previously explained, the marginal cost of energy conservation has been identified in two different ways for new and existing buildings, respectively. For new buildings, the marginal cost represents an increased investment in all new buildings, since the least-cost solution is to be found when all new buildings are insulated to the same level. However, for existing buildings this is not the case, because investments in conservation are only relevant when renovation is being carried out anyway. Therefore, the least-cost solution (within a certain number of years, i.e. till 2050) is identified as a scenario in which the buildings being renovated include all energy conservation measures, while buildings not being renovated are left more or less as they are. Consequently, for existing buildings, the marginal cost represents investments in an increasing

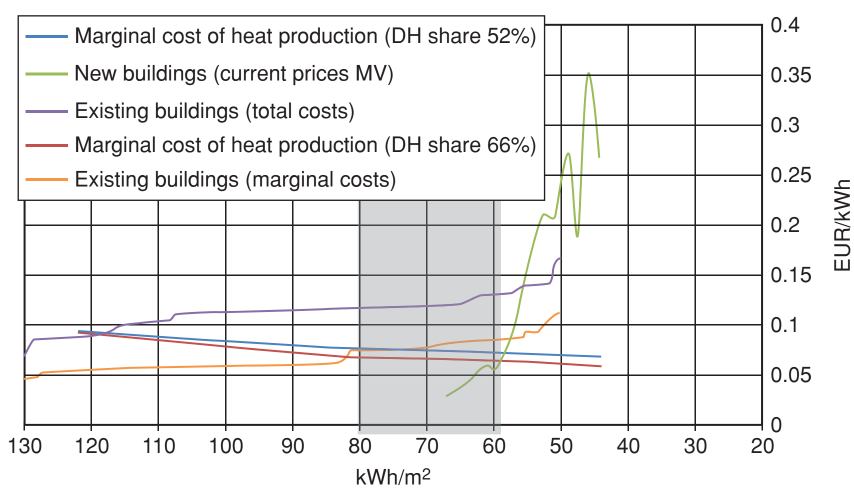

Figure 5: Marginal cost of heat production in the overall energy system in year 2050 compared to the marginal cost of improving the energy efficiency in a new building, an existing building (total costs) and an existing building being renovated anyway (marginal costs). New buildings are here represented by a 150 m^2 single-family house and existing buildings as the total m^2 of single-family houses, farmhouses and terrace houses. Both are shown as a function of the average heat demand per unit in the buildings.

number of buildings. The increased marginal cost illustrates the fact that in old and not renovated buildings, one can achieve more savings for the same money than in new and/or renovated buildings. This also corresponds well with the fact that the old buildings are likely to be the ones that will be renovated first.

For the same reason, the diagram includes the phenomenon that the marginal cost of new buildings ends up being higher than that of existing buildings when measured in EUR/kWh. Thus, for the existing buildings, this part of the curve still includes energy conservation of the full spectrum of buildings, from the existing level to the level of low energy buildings. In principle, some of the "expensive" measures in existing buildings are already part of the mix in the beginning of the curve, leaving a small portion of the "cheap" measures to the end of the curve and therefore the ability to become cheaper than new buildings.

In principle, this is a contradiction since, theoretically, one would then be able to identify a cheaper solution in which only the "cheaper" measures were implemented. However, the curve shows that in practice this is not possible, since the "cheap" measures can only be implemented when the building is being renovated, and not all buildings are being renovated during the period of time in question. Therefore, some "cheap" measures can still be introduced in the existing buildings (and not the new) after implementing the optimal least-cost strategy.

Figure 5 shows demands per unit (kWh/m^2). However, the identification of least-cost strategies also has to do with the share of existing versus new buildings in the 2050 scenario. Consequently, to supplement Figure 5, a calculation has been made on the basic assumption of a 40% expansion of new buildings from 2010 to 2050. The results are shown in Figure 6 as a function of absolute heat demand (TWh/year). Again production costs are shown for two district heating shares. Savings in existing buildings concern 50 TWh/year and can decrease by approx. 32 TWh/year, while new buildings concern 20 TWh/year and can decrease by approx. 14 TWh/year. Merging the curves of existing and new buildings into one, the curve concerns 70 TWh/year and can decrease to 25 TWh/year. However, as can be seen, the least-cost solution is to be found with a 42% cut from 70 TWh/year to approx. 40 TWh/year. Again, since the data only takes into account buildings accommodating only one family, the cut should be expected to be closer to 50% than the shown 42%.

The shade in Figure 5 highlights the difference between feasible savings in existing buildings and new

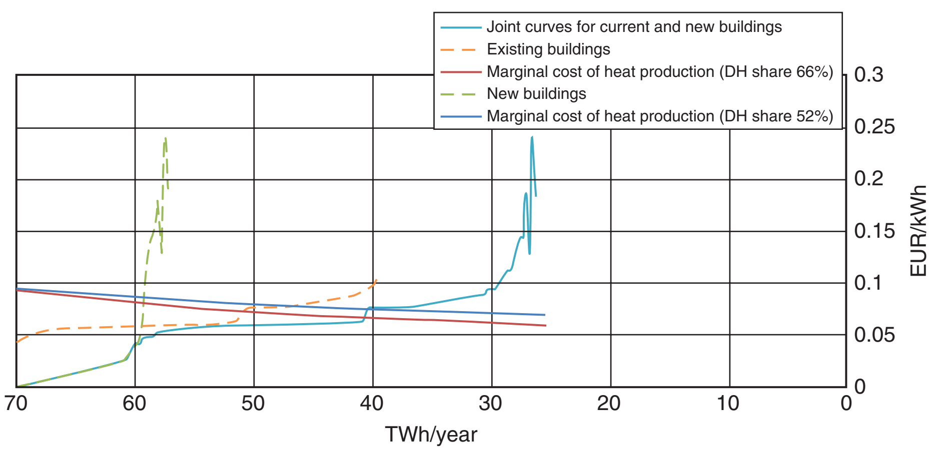

Figure 6: Marginal cost of heat production in the overall energy system in year 2050 compared to the marginal cost of improving the energy efficiency in buildings in a scenario in which the building stock is increased by 40% from 2010 till 2050. New buildings are here represented by a 150 m^2 single-family house and existing buildings as the total m^2 of single-family houses, farmhouses and terrace houses. Both are shown as a function of the total net space heating and hot water heat demand in the buildings.

buildings. This could indicate that the result might be a little sensitive to the future mix of new and existing buildings, because of the difference between 58 kWh/m^2 and 80 kWh/m^2. However, since the analysis does not include apartments and offices, the cut off for existing buildings should be lower; thus minimizing the sensitivity of the future mix between existing and new buildings.

The above-mentioned calculation has been carried out with a real interest rate of 3%. Sensitivity analyses of 1% and 5%, respectively, show that both total costs and marginal cost are sensitive to the interest rate, since a significant part of the costs are investments. The analysis is not particularly sensitive to a decrease in the costs of investing in saving measures in the buildings. A sensitivity analysis has been carried out with potential future cost reductions. However, due to the steep rise in marginal costs related to savings, the potential lower costs will have only a minor influence of around 3% on the least-cost optimal point. However, one issue was found to be of outmost importance, namely the issue of mechanical ventilation. The cost of mechanical ventilation as well as the condition whether or not this cost is considered part of the energy saving cost highly influence the results.

5. Conclusion

This paper has presented a methodology to identify least-cost strategies for reducing the heat demand of buildings as a part of implementing sustainable smart energy systems. The methodology has then been applied to the case of Denmark.

Based on the detailed hourly modelling of a proposal to implement the Danish governmental strategy of an energy system based on 100% renewable energy by year 2050, the future marginal costs of producing heat have been identified. The marginal heat production costs have then been compared to similar marginal heat savings costs.

The important point which is emphasised in this paper is that the size of the investment costs strongly depends on whether energy conservation is done in existing buildings or as additional investments in new buildings. Furthermore, it depends on whether investments are made solely for the purpose of reducing the heat demand or as an integrated part of a renovation which will take place anyway. Moreover, the identification of proper strategies depends on the marginal alternative production of the energy system, and the cost of this marginal production again depends on which system one addresses. For existing buildings, the data includes all types of buildings, while new buildings have been represented by single-family houses.

Further, the analysis highlights the importance of identifying long-term heating strategies since least-cost solutions require a long period of implementation. First, savings should mostly be implemented when buildings are being constructed or when renovations are being carried out anyway, which requires several decades to cover the building stock. Second, a suitable district heating infrastructure should be developed and adjusted to low-energy buildings, which also calls for a long time horizon.

For Denmark, a suitable least-cost heating strategy seems to be to implement savings in new buildings and buildings which are being renovated anyway. Savings should be implemented to an extent that will decrease the net heat demand of space heating and hot water by approximately 50% compared to the present level, while heat savings in buildings which are not being renovated hardly pay. Moreover, the analysis points in the direction that a least-cost strategy will be to provide approx. 2/3 of the heat demand from district heating and the rest from individual heat pumps.

It should be emphasized that such a future heat saving strategy is very ambitious compared to previous years. Thus, a similar development in specific heat demands for the previous 40 years shows only a 17% per cent decrease from 147 kWh/m^2 in 1970 to 122 kWh/m^2 in 2010. This historical development emphasizes the fact that the implementation of a 50% cut during the next 40 years is very ambitious and will require an active policy.

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