Future Green Buildings

A Key to Cost-Effective Sustainable Energy Systems

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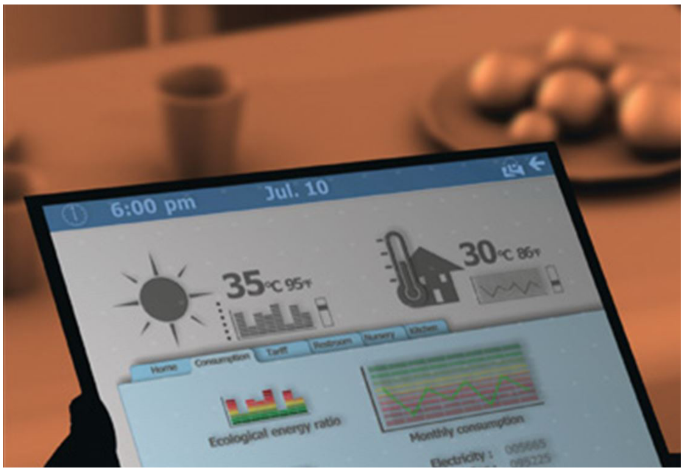

RENOVERING PÅ DAGSORDENEN

AALBORG UNIVERSITY
DENMARK

Future Green Buildings
– A key to Cost-Effective Sustainable Energy Systems

Danish title: Fremtidens byggeri - Nøglen til et omkostningseffektivt og bæredygtigt energisystem

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Renovering på Dagsordenen:

Bygherreforeningen
Foreningen af Rådgivende Ingeniører - FRI
Dansk Byggeri
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- **Bygherreforeningen (Danish Association of Construction Clients – DACC)**
- **Foreningen af Rådgivende Ingeniører - FRI (Danish Association of Consulting Engineers)**
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- **Danske Arkitektvirksomheder (Danish Association of Architectural Firms)**
- **Ingeniørforeningen IDA (The Danish Society of Engineers)**

The partnership also consists of: Grundejernes Investeringsfond GI (The Landowners' Investment Foundation), Konstruktørforeningen KF (The Danish Association of Building Experts, Managers and Surveyors), COWI, MT Højgaard, NCC and Realdania.

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Foreword

There is an increasing understanding in the public debate, as well as in the buildings and energy sector, that the times in which savings, heating, cooling, electricity, transport and gas could be seen as separate parts of energy system are over. In renewable energy systems, sectors need to be integrated. The understanding of the roles of the individual technologies is crucial. Buildings play a central role on the demand side in the future energy system. On the one hand future green buildings cannot be seen alone, on the other hand the renewable energy system cannot be looked upon without considering buildings and their users. This report aims to provide a direction for the development of buildings in and towards cost-effective renewable energy systems. The role of buildings needs to be understood better: How far should we go with savings? What is the role of flexible demand or storage at the building level? To what extent should on-site renewable energy production be the solution?

The partnership ”Renovering på dagsordenen” (Renovation on the Agenda) represents a very wide range of organisations and companies within the building sector in Denmark. The partnership has an interest in providing a better understanding of how future green buildings should perform in renewable energy systems. Long-term investments are made continuously on the demand and production side in the energy system. Buildings should not only function today, but also contribute to cost-efficient solutions and existing buildings will play a major role in the future.

This report “Future Green Buildings – A key to cost-effective sustainable energy systems” is supplemented by a short Danish summary titled: “Fremtidens byggeri – Nøglen til et omkostningseffektivt og bæredygtigt energisystem”. The report is prepared by researchers from The Sustainable Energy Planning Group at the Department of Development and Planning at Aalborg University. The project was carried out in the period from February to May 2016. The report can be downloaded from www.vbn.aau.dk.

A workshop with key participants from “Renovering på dagsordenen”, Aalborg University – Department of Development and Planning, and Aalborg University – Danish Building Research Institute (SBi) was carried out as part of the process in March 2016. The participants were: Thomas Uhd, Bygherreforeningen; Graves K. Simonsen, Bygherreforeningen; Annette Blegvad, Arkitektforeningen; Peter Andreas Sattrup, Danske Arkitektvirksomheder; Michael H. Nielsen, Dansk Byggeri; Pernille Hagedorn-Rasmussen, IDA; Henrik Garver, FRI; Søren Aggerholm, SBi; Per Heiselberg, AAU; Kirsten Gram-Hanssen, SBi; Henrik Lund, AAU; Jens Stissing Jensen, AAU; Brian Vad Mathiesen, AAU.

While Denmark is well on the way to having renewable based electricity and heating sectors, a number of challenges still exist within energy storage, transport and the integration of the energy sectors. The aim here has been to collect state-of-the-art knowledge about the role of buildings in this context, present the technical possibilities that are available and to inspire short-term decision-making based on this.

On behalf of the authors, Brian Vad Mathiesen, May 2016

Executive Summary

Similar to today, efficient buildings are essential for an affordable Danish energy supply in 2050. The purpose of this report is to describe the contribution and role of the building sector in a 100% renewable energy future, as well as the transitions that are necessary in the building sector to support this change. The report builds on a literature review encompassing more than 50 reports and research papers over the last 10 years and more than two decades of knowledge about the interactions between different components of the energy sector. The review has been focused on aspects such as cost-effective solutions from an energy system integration perspective, heat savings, electricity savings, and user behavioural aspects as well as energy storage and household level flexibility.

Many reports on green or sustainable buildings focus only on savings levels and disregard the cost of renewable energy production. Some reports focus on building level on-site renewable energy production, optimising storage for passive houses, or net-zero emission buildings. In an integrated energy system, the question is, how far should we go with savings? What is the role of flexible demand or storage at the building level? And to what extent should on-site renewable energy production be the solution?

Stakeholders associated with the buildings sector need to support such a transition because the use of buildings, renovation and expansion should facilitate an increasingly lower electricity and heat demand, while also enabling cost-effective and flexible systems to supply energy to the building.

The key to understanding the future role of existing and new buildings is to understand the changes around buildings in the next 34 years in the energy system. A number of reports have looked at scenarios towards 2050, including the Danish TSO, Energinet.dk (2015) and The Danish Energy Agency (2013). Research on identifying a balanced approach to supply side and demand side measures from a system perspective has been conducted in a number of analyses since 2006[1]. The latest report using system level knowledge and research is the IDA Energy Vision 2050 (IDA-Danish Society of Engineers)[2]. In this report we take this vision for Denmark as the point of departure, however similar developments for the energy system and role of buildings can be found in other reports. Other countries in a similar transition process may find the recommendations and results useful.

The IDA Energy Vision 2050 concludes that 100% renewable energy in 2050 is technically possible and economically feasible. This transition can also be done cost-effectively and with a sustainable use of biomass by using a Smart Energy System approach. This approach entails using synergies in savings, energy efficiency, interactions between sectors and with an integrated use of storage as well as existing infrastructures. The contribution of the building sector is essential to establish smart energy infrastructures and a 100% renewable Denmark. If done, the overall transition towards 2050 can create 50,000 jobs/year domestically within a wide range of skills, from carpenters to wind power

[1] *Ingeniørforeningens Energiplan 2030 – baggrundsrapport*; Lund H, Mathiesen B V. Ingeniørforeningen i Danmark, IDA, 2006. *Varmeplan Danmark*; Dyrelund A, Lund H, Möller B, Mathiesen B V, Fafner K, et al. Aalborg University, 2008. *Varmeplan Danmark 2010*; Dyrelund A, Fafner K, Ulbjerg F, Knudsen S, Lund H, Mathiesen B V, Hvelplund F, et al. Aalborg University, 2010. *IDA´s klimaplan 2050 – Baggrundsrapport*; Mathiesen B V, Lund H, Karlsson K. Ingeniørforeningen i Danmark, IDA, 2009. *Coherent Energy and Environmental System Analysis (CEESA)*; Lund H, Hvelplund F, Mathiesen B V, Østergaard PA, Christensen P, Connolly D, et al. Aalborg University, 2011. *Heat Saving Strategies in Sustainable Smart Energy System*; Lund H, Thellufsen J Z, Aggerholm S, Wittchen K, Nielsen S, Mathiesen B V, Möller B. Aalborg University, 2014.

[2] *IDA's Energy Vision 2050 : A Smart Energy System strategy for 100% renewable Denmark*; Mathiesen B V, Lund H, Hansen K, Ridjan I, Djørup S R, Nielsen S, Sorknæs P, Thellufsen J Z, Grundahl L, Lund R Søgaard, Drysdale D, Connolly D, Østergaard P A. Aalborg University, 2015.

engineers. In addition, there is a significant potential for jobs from increased technology export as well as the side effects of lower emissions and lower Danish health costs.

Today, buildings account for around 41% percent of the total end-use energy demand in Denmark (see Figure 1). This constitutes mainly heating, hot water and electricity demands in appliances and cooling. With such a large use of resources in buildings, reductions in electricity and heat demands as well as changes in the energy supply are essential for a cost-effective future 100% renewable energy system. Recommendations to conduct energy savings and support behavioural changes in the operation of buildings go hand in hand with supply level recommendations. District heating should be expanded further to replace individual boilers and new supply systems with lower temperature district heating from solar thermal, large-scale heat pumps, geothermal, waste incineration, and biogas. should be supported. Outside district heating areas, efficient ground-source heat pumps supplemented with solar thermal can be recommended.

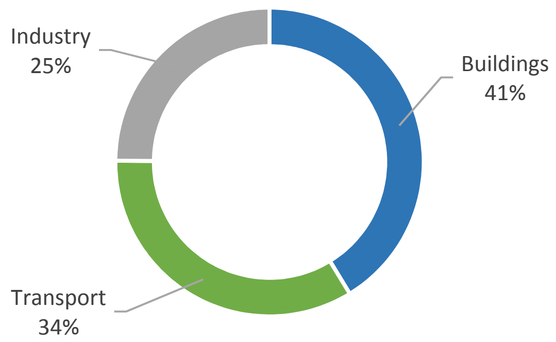


Figure 1: Breakdown of the total end-use energy demand between different sectors in Denmark

Currently, we have very strict energy performance levels for new buildings from 2015 and 2020. This however does not solve the problem we need to address in the building stock in general, because savings and low energy use in new buildings cannot reduce energy demands to a level sufficient for the energy system, and focus on new building seems to take focus away from existing buildings and the importance of electricity and heat savings there. In addition, the performance levels are strict and shaped so that they promote the installation of on-site energy production units to offset energy consumption. This means that production units are installed on buildings which may not always be cost-effective and beneficial to renewable energy on the larger scale. Additionally, it isolates the buildings from the system and makes cooperation between neighbours more difficult regarding heat supply for example. Photovoltaic (PV) should be promoted and is highly needed for electricity production on the system level. This however must not result in lower building insulation levels and it must not result in a promotion of household level batteries to shift their production from one hour to another. Both lower levels of insulation and suboptimal integration of storage can be extremely expensive.

Three separate perspectives have been identified as key for the building sector in a 100% renewable energy system. Firstly, greater energy efficiency in the whole stock is crucial to enable a renewable, flexible energy system, especially in existing buildings. Secondly, the operation and user-behaviour of people in buildings is a crucial element to achieve savings in

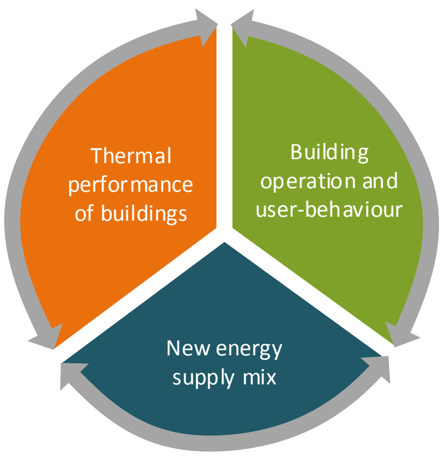


Figure 2: Three perspectives key to the role of buildings in future cost-effective sustainable energy systems

heat and electricity demands over time. The third is the supply mix of energy, where buildings have an important role in opening up possibilities for more efficient use of renewable energy and more flexible energy sources in infrastructure and storages in other parts of the energy system.

While these three points are separate elements for cost-effective green buildings of the future, they are closely and inseparably intertwined, to the point that the one is impossible without the other. In many cases parallel developments are required in order to unlock the potential contribution that buildings can have in a renewable energy future.

Thermal performance of buildings

An important point of departure for understanding the role the Danish building stock is that newly built houses only play a relatively small role due to the long lifetime of existing buildings. Only approximately 1-1.5% of the housing stock is newly built each year, most of which represents growth in the housing stock rather than replacement. Most of the buildings that are important in terms of saving energy from today to 2050 have already been built. A strategy for increasing the technical energy efficiency of the building stock must therefore have the existing building stock as its primary target.

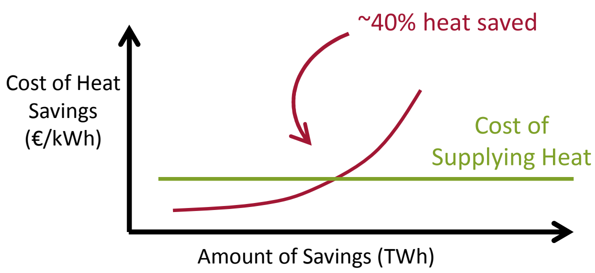


Figure 3: Simplified diagram which shows that energy renovations should only be invested in until the point in which the cost of supplying heat to the building is cheaper than further renovations. In the Danish building stock ~40 of heat demand per square metre should be saved in existing buildings

The most important contribution of the building stock is efficiency improvements and energy savings concerning the use of heating, cooling and electricity in the buildings. Energy saving strategies should be preferred as long as the marginal cost of realising these energy savings is lower than the marginal cost of increasing the renewable production, both with regard to electricity and heat (see Figure 3). In the IDA Energy Vision 2050, the recommended magnitude of heat savings in existing buildings should reach an average of approximately 80 kWh/m²/year depending on type and age, compared to an average of 132 kWh/m²/year in 2015[3]. This ensures that all houses can be renovated to a point of efficiency that makes sense for the type of building at hand, rather than focusing on investments towards integrated renewables in one building, which are typically not cost-effective from a system point of view. Given the gains necessary to bring the entire building stock to at least 80 kWh/m²/year, a broad, long term strategy taking into account the entire building stock is necessary. If heat savings are not achieved to the level suggested here, the primary energy supply in the system may increase by 16 TWh/year (58 PJ) and the costs may increase by approximately 2 billion DKK/year. Moreover, the heat savings in the buildings are important for the system, since they pave the way for low-temperature heating supplies. These are essential for both future district heating solutions as well as individual heap pumps.

Within the building sector, the focus should be on renovating pre-1980 buildings, which do not perform nearly as well as buildings built under more stringent Building Codes. Implementing heat savings on their own is in general so costly that from a socio-economic point of view, this cannot be

[3] The kWh/m² includes space heating and use of hot water, but excludes electricity consumption as well as onsite energy production such as solar thermal or PV.

recommended. It is essential that heat savings in existing buildings is implemented together with general renovation and refurbishment. Since the frequency of general refurbishment activities is 20-50 years it is critical that energy savings are systematically addressed in relation to all refurbishment activities. Otherwise, the cost of achieving demand savings is excessive and a renewable energy system by 2050 is most likely more costly.

In terms of actions required and the challenge to reach the target - which from an economic point of view is cost-effective - even going halfway is extremely ambitious. It is unlikely to happen without serious initiatives and a strong policy framework. Since 1980, the building stock's final energy consumption per square metre for space heating and hot water has decreased by approximately 35% in the past 35 years, while the total floor space increased by approximately 40%. The ambition for the next 34 years should be to accelerate reductions in the final energy consumption of the building stock. For the building stock that exists today this means that approximately 40% savings can be recommended for space heating (including hot water).

Although new buildings pose a smaller challenge overall, it is key that recommendations are made which facilitate savings to a level at which supply with renewable energy becomes cheaper. In the IDA Energy Vision 2050 it is recommended that heat demands in new buildings reach a level of ~55 kWh/m^2.

Figure 4: Operation of the buildings should account for technology, user knowledge, habits, and norms (meanings)

Building operation and user-behaviour

User practices have a decisive influence on the actual use of energy in buildings, so a change in buildings' energy demand though new technical installations will have to include changing the way that people interact with and use buildings. For example, 1) the 'pre-bound effect': residents in dwellings with a low technical energy standard may keep a relatively low indoor temperature, or they only keep part of their house heated; and 2) the 'rebound effects': residents in dwellings with a high technical energy standard may develop less energy efficient practices.

Energy efficiency cannot be seen merely as a technical exercise. Technological changes such as insulation, smart meters, thermostats, on-site energy production etc. must be accompanied by behaviour altering measures that will actually result in lower energy consumption in the operation phase. This can include smart meters and other behavioural considerations around building users' knowledge, habits and norms (meanings)[4].

In terms of the overall flexibility of the system and ability to integrate intermittent renewable energy sources, both system level flexibility and flexible demand and storage in buildings are considered. System flexibility, based on the aggregation of demand and integration between sectors as described in the IDA Energy Vision 2050 and Smart Energy System concept, is cheaper to achieve than flexibility and storage at the building level. While passive storage of heat in the buildings may be used cost-effectively, the potential is limited. It is more important to have low energy use in the operation of the buildings - and a shift from boilers to heat pumps or district heating - than to focus on flexibility on the building level. While flexible demand of electricity and heat may contribute to reducing peaks for production plants, savings can reduce peaks more consistently in the operation phase. Flexibility

[4] Gram-Hanssen K. Housing in a sustainable consumption perspective. In: Reisch LA, Thøgersen J, editors. Handb. Res. Sustain. Consum., Cheltenham, Massachusetts: Edward Elgar Publishing; 2015, p. 178–91

and storage should focus on the integration of the electricity, heat, cooling and transport sectors. Sending price signals via the electricity market to homes is an expensive and inefficient way of providing flexibility looking at the challenge in the overall system transformation. Electrification of district heat, transport and production of hydrogen by means of electrolysis can provide more cost-effective flexibility services and storage than single buildings.

The risk of promoting batteries on the household level is high - which is problematic - if careful consideration is not put into regulation of PV, electricity levies and the buildings codes. The economic costs of storage of electricity in batteries with the purpose of bringing electricity back onto the grid is very high due to two reasons. Firstly, electricity may be stored in the building when electricity demands elsewhere are high and being met by fossil fuel power plants, hence not actually stopping power plants. Secondly, using electricity at night from batteries decreases the use of electricity from the grid at times when other renewables may be abundant, demands are low in general and prices are low. In addition, battery storage in itself is an extremely expensive form of storage, with electricity storage being costlier by a factor of 100 compared to thermal storage, and more than a factor of 1000 compared to gas and liquid fuel storages.

Efficiency and heat, cooling and electricity savings is more important than for buildings to have energy storage or balancing capacity. Buildings' largest contribution to a 100% renewable energy system is through efficiency; by lowering the total energy needed, by lowering the peak energy needed, and in the case of thermal energy by lowering the temperature at which heat is required through more efficient buildings, and increasing the retention of heat in the building envelope. Building regulations, tariffs, and innovative smart developments should be focused on reducing energy consumption, enabling low temperature district heating, and on peak shaving through passive heat storage.

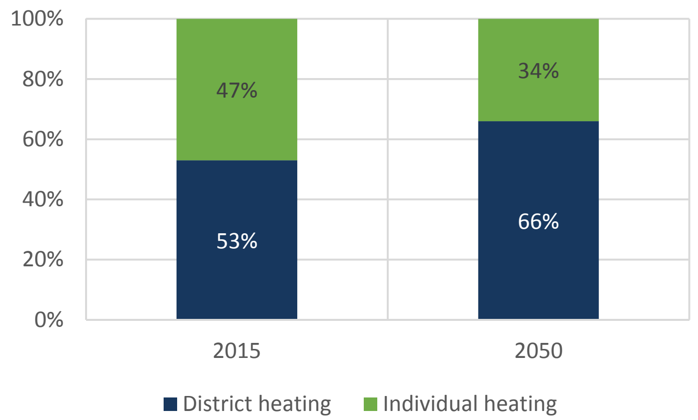


Figure 5: Proportion of total heat supply split between individual heating and district heating

New energy supply mix

Understanding the energy supply-side of buildings is crucial for making effective decisions on energy use in buildings. Technologies such as large-scale heat pumps for district heating, low temperature district heating, large heat storages and ground source heat pumps actively help integrate renewable energy into the energy system cost-effectively. These supply side options go hand in hand with efficiency measures in the operation of buildings. In the IDA Energy Vision 2050 these infrastructures represent the link

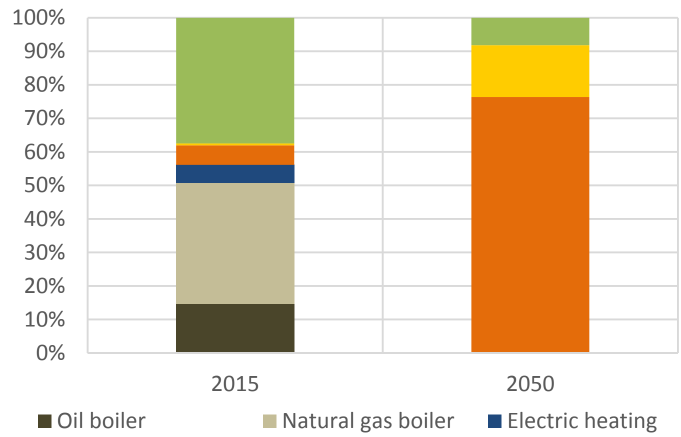


Figure 6: Breakdown of heat supply technologies within buildings

between the thermal (heating and cooling) and electricity sectors that underpin the Smart Energy System, and the system flexibility in the storage options provided. The more efficient the building stock is, the more synergies and benefits can be created for the overall system, which may consist of three times the amount of wind power we have today. It is feasible that the electricity mix may have more than 80% fluctuating renewable energy sources in 2050.

District heating coverage should be increased also to new buildings depending on local costs and local conditions (Figure 5). Cost-efficiency is associated with replacing boilers with district heating and ground source heat pumps. The use of biomass boilers should not be promoted; however, some installations will be present (Figure 6). Lower temperature demands in the buildings increase the efficiency in all these supply options.

Where feasible, solar thermal should be installed to supplement ground source heat pumps or biomass boilers. PV is an important part of the future energy system. PV should be promoted with a balanced scheme so cost-optimal installations are installed which in some cases are on buildings, in others on fields. To ensure the renovation of existing buildings and new buildings is achieved sufficiently, the demands for the building insulation level and the installation of solar thermal or PV should not be mixed in the regulatory and policy framework.

Key points & recommendations

Thermal performance of buildings

- In the future, the same as today, buildings will be responsible for a large proportion of heating, cooling and electricity demand in the energy system. However, in the future, the energy system must consume less to achieve the 100% renewable goal, meaning that it is **essential that the building stock is part of the energy transition** through energy savings. Overall existing buildings should reduce their total space heating energy consumption by around 40% between today and 2050 (including hot water). The total electricity demand from the building stock should remain at the same level as today, even with more buildings and electric heat pumps. This means electricity savings should still be promoted in new appliances. Energy efficiency and energy savings in the building stock will lower the total amount of energy required, increase retention of heat in the building envelope, lower the peak energy demand levels, and lower the temperature level required from heat supply technologies. This is very important for the overall performance of the system.

- Between 1-1.5% of the building stock is newly built yearly. Most of these buildings represent a growth in the building stock rather than replacement, which is only around 0.25% per year. In total it is expected that new building floor space will increase by around 25-30% from today until 2050. The buildings built today are required to be highly energy efficient according to the BR15. This means that for the building stock as such, **it is less important to place focus on new buildings to save energy in the future energy system**, since very little renovation activities will need to be done until 2050 for these buildings.

- Around 90% of the building stock existing today will exist in 2050. Therefore, **energy savings need to be made in the existing building stock**. To have a cost-effective energy system it is a prerequisite that existing buildings reduce total heating energy consumption by around 40% between today and 2050. This means the average heat demand per square metre for the existing building stock should be reduced by around 1.5% per year until 2050. In the last 15-20 years the average heat demand per square metre has been decreasing at around 0.8-1% per year. This means that an increase in renovation rates for existing buildings is necessary. If this is not achieved by 2050, the need for biomass may exceed the available biomass in Denmark or more wind turbines and PV may be required. This will eventually lead to risks related to energy security of supply and certainly higher costs of the energy system.

- **Renovations should be targeted at the worst performing buildings first.** A detailed list of buildings to be renovated has not been provided in this report. However, based on this assertion, most renovation activities in existing buildings should be done in buildings built prior to 1980, especially for older buildings such as individual detached houses built in the early 20th century.

- There is a very specific and limited window of opportunity to implement energy renovations in existing buildings. It is essential that **energy renovations are done when renovations are already being carried out** on specific parts of the building, for example, roofs and windows. This is because it is not cost-effective to do energy renovations by themselves. Certain policy measures would likely be needed to encourage this activity.

Building operation and user-behaviour

- Heating and electricity savings will likely not be achieved if only technical energy renovations are carried out in the building stock. It is necessary to **consider and address connecting technical energy renovations and operation (smart meters) to user behaviour in the building.** Electricity savings are mostly achieved through improved building operation and user-behaviour.

- Heating and electricity savings should be achieved with improved operation of the building (i.e. via smart meters, better appliances, thermostats etc.) and consumer behaviour. **Behaviour and user operation is key to the performance of buildings**, to the extent that end use of energy in identical buildings may vary by a factor of three. The pre-bound and rebound effects mean that even if buildings are renovated, the energy savings are not guaranteed. To address this appropriately when installing energy renovations and other technologies such as smart meters (that provide different information to the user or system operator), it is essential that three factors are considered: user knowledge, habits and norms (meanings). If these factors are addressed in isolation, not addressed, or not addressed together the chances of achieving heat and electricity savings are likely to be reduced.

- To optimise the potential of user-behaviour and operation of the building, it is important that the **operation of the buildings is according to the needs of the energy system**, and not optimised to the needs of the individual building. This is because the energy system in the future will be highly integrated, and for the energy system to operate properly it will depend heavily on the appropriate operation of the buildings. This means that buildings should not operate in isolation from the rest of the energy system or be optimised on its own.

- **Buildings should not be prioritised as a source of flexibility in the energy system** since the flexibility can be provided by cheaper means and more efficient technologies in other parts of the system, for example large-scale heat pumps, electrolysers, and large-scale thermal storage. Smart meters or flexibility in using e.g. heat pumps or regulation the heat demands have a potential to make contributions to reduce peaks for power plants and in production of district heating. The potential for integrating large quantities of renewable energy by using this flexibility is limited.

- There is **limited room for building level flexibility**, **building level energy storage and using integrated energy supply as a way to offset building level energy consumption (nZEBs).** Flexibility and energy storage services can be achieved more cost-effectively and with more success at the system level rather than the building level. Studies demonstrate that investment in passive heat storage is a cost-effective way of providing flexibility, but investments in heat accumulation tanks and batteries on the household level are not cost-effective. Energy savings in buildings are more important than building level flexibility.

New energy supply mix

- The flexibility required to integrate fluctuating renewables is realised by integrating the thermal, power and transport sectors towards 2050. The improved efficiency in the building stock will help create synergies between these sectors in the wider energy system, by allowing more integration between the thermal and power sectors. With increasing fluctuations in the electricity supply caused by wind power and PV, this calls for solutions to increase the flexibility of the system. **Buildings can contribute to a Smart Energy System by enabling a new interplay with energy supply technologies that maximise the synergies in the system, such as (low-temperature) district heating and in some buildings district cooling in dense areas, and individual heat pumps in less dense (rural) areas.** By utilising these two technologies this means that more benefits can be achieved at the system level by integrating more renewable energy technologies and cheaper energy storage technologies.

- **Individual micro-CHP options or biomass boilers do not seem to be desirable,** neither in terms of fuel efficiency nor from an economic point of view. Biomass boilers however will be used to some extent in the future although biomass can be allocated better to other purposes than heating and used more efficiently.

- It is cost-effective for the energy system to **increase the share of district heating from around half of the heat supply today to around two thirds in 2050**. This is based on analysis that used GIS mapping to determine the costs of installing new pipelines and district heating infrastructures as well as energy system analyses. Moreover, the expansion of district heating will help utilise heat production from waste incineration and industrial excess heat production, geothermal heating, biogas production (supply of heat), and solid biomass such as straw.

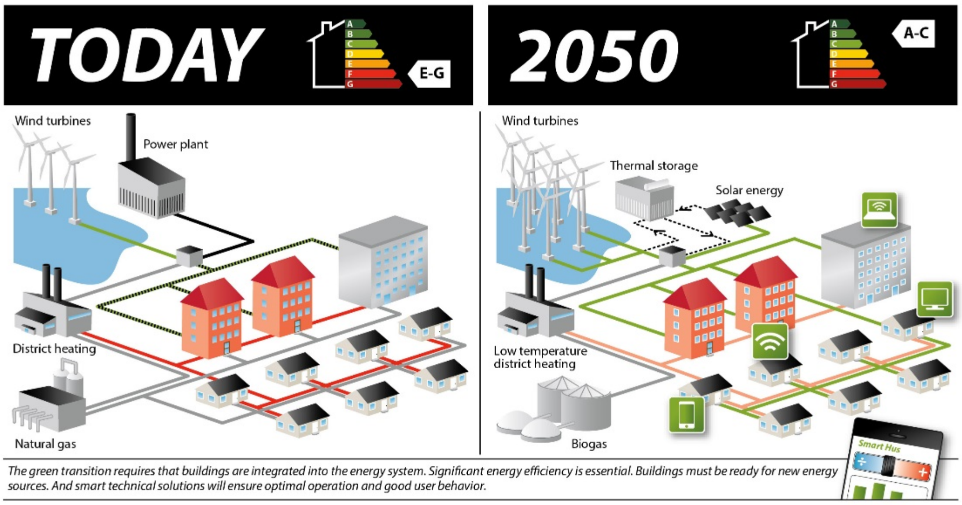
- Coupled with increased district heating and heat savings in buildings, the temperature of the **heat supplied to the buildings can be gradually decreased towards 2050** to save primary energy demand but also to enable integration of new renewable energies, excess heat from industry, large-scale heat pumps and energy storages at the system level. It is uncertain how the buildings will need to be upgraded to receive lower temperature district heat since this research is ongoing, but it is likely that most radiators installed today will be sufficient in the future. Smart meters could facilitate good solutions and help monitor changes in the operation of the building.

- **Individual heat pumps seem to be the most cost-effective alternative to district heating for buildings too far from district heating grid**. This is because heat pumps provide external benefits to the energy system through high energy efficiency, by electricity consumption, and by having some level of flexibility. They are the individual heating alternative that fits best into a cost-effective 100% renewable energy supply, also because they place the least pressure on the amounts of biomass and wind required in the system. Ground-source heat pumps should be promoted as the COP is higher than air-air heat pumps during the colder winters. On-site solar thermal heat production units should be installed on buildings to assist heat production units such as heat pumps or biomass boilers.

- It is important that **energy efficiency and building integrated energy production are regulated independent from each other** in order to avoid that for example the installation of PV, solar thermal or individual heat pumps will lead to less renovation levels and decreased energy performance in the building.

- The future energy system will have a higher share of PV, with at least 5000 MW capacity installed, however it is **important that PVs (and other electricity producing units) are installed where it is**

most cost-effective and appropriate for the energy system. It is not necessary to install solar PV on all buildings, and it can be inefficient to install solar PV on buildings in order to offset in-building energy consumption (for example in nZEBs). All electric energy production units should remain connected to the grid and interact with the system. In addition, on-site electricity storage should be avoided since this is not beneficial to the system and leads to higher energy system costs.



Thermal performance of buildings	Level of heat demand in existing buildings	Low, medium and high	Low
	Level of heat demand in new buildings	Very low	Very low
Building operation and user-behaviour	Level of appliance electricity demand	Medium	Low
	Level of heat pump electricity demand	Low	Medium
	Energy-efficient user practices	Limited	Medium
	Building level flexible demand	None	Very limited
	On-site electricity production and own-use	Very limited	Very limited
	On-site electricity storage	None	Very limited
New energy supply mix	Level of district heating coverage	High	Very high
	Low temperature district heating	None	High
	Large scale heat pumps	Low	High
	Individual heat pumps	Low	High
	Individual boilers	High	Low

Figure 7: Three key perspectives in which the Danish building stock will be more involved in the future energy system

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1. Introduction to the report

Over the past 40 years, Denmark has devoted a lot of effort towards energy and climate and maintains its goal to transition to a 100% renewable energy future. Over the next 34 years, as the energy system shifts to 100% renewable energy, this will create new dynamics between the building stock and the energy system. Achieving these changes will require a system level energy dialogue about energy savings and the uptake of renewable energy technologies for electricity, heating and transport. The building stock, as a key sector of the energy system, cannot be ignored in this transition.

The Danish building stock is an important part of the energy system today, as it consumes large amounts of energy for heating, cooling and electricity. This means that as the energy system moves from a largely fossil-based energy system to a renewable-based energy system, it is essential that the building stock is involved in the transition. If the building stock is not addressed and changed appropriately, there is a greater risk of not succeeding in achieving a sustainable energy system.

So far, the details of the specific role that buildings will have in a 100% renewable energy system have been unclear. Nearly all roadmaps, strategies, and visions imply a huge amount of savings and efficiency in the building stock, and make clear the urgency of reducing buildings' energy use [1–8]. All the studies require high heat and electricity savings in Danish homes and buildings, otherwise it will be difficult to install enough wind turbines and have low enough biomass demand to achieve the energy system transition. Additionally, innovations regarding the operation of buildings and strategies for influencing consumer behaviour create an expectation for buildings to become adaptable, flexible, active parts of the energy system. In these ways it is clear that buildings will have to evolve and change as part of a wider energy transition.

However, it is not always clear what the overarching strategy and role for the building stock should be, and what priorities are most important in the context of the energy system. Using research on the Danish energy system and buildings, this report aims to address how the role of buildings will change in such an energy transition.

1.1. Purpose

The purpose of this report is to provide a research-based reference guide on buildings, addressing what the role of buildings will be in a 100% renewable energy system. To do so a brief description is given of what the future energy system will look like, what specific roles that the building stock is likely to have in such a future renewable energy system, and provide some recommendations for how to move forward.

The aim of this report was to clarify some key questions that have been raised in connection to the building stocks role in a future renewable energy system. The report is particularly focussed on providing some answers to the following questions:

- How far should we go with energy savings?
- What is the role of flexible demand or storage at the building level?
- To what extent should on-site renewable energy production be the solution?

As an outcome, certain key recommendations are provided for the partnership "Renovering på dagsordenen" about the ways in which the building stock needs to adapt and integrate with the transitioning energy system. The recommendations are valuable not only for the partnership but also for others with interest to ensure that the appropriate decisions and policies are put into place to enable the successful transition to a 100% renewable energy system.

1.2. Methodology

This report is the result of a literature review covering academic reports and peer-reviewed papers, including many developed at Statens Byggeforskningsinstitut (SBi, the Danish Building Research Institute), and the Sustainable Energy Planning Research Group at Aalborg University.

Much of the data for the analysis and recommendations in this report are based the IDA Energy Vision 2050 [1] from 2015, herein referred to as the "IDA Energy Vision". The transition to a 100% renewable energy system has been studied in a Danish context in several ways over the past few years [1–8]. Many of the scenarios, including the IDA Energy Vision, have common features, primarily relying on a combination of wind energy and energy efficiency improvements.

While it is one of several 100% renewable Denmark scenarios, the IDA Energy Vision has been chosen because of its emphasis on cost efficiency and robustness. The IDA Energy Vision includes a variety of sensitivity analyses. These allow for an in-depth investigation of different influential factors; for example, what role savings in buildings will play in the system, and an analysis of which technologies can most cost-effectively provide heating. The developed 2050 energy scenario in the IDA Energy Vision, as well as the knowledge gained from the sensitivity analyses, has been used as the main framework for the analysis and recommendations.

The IDA Energy Vision provides a feasible and cost-effective Smart Energy System strategy and a roadmap to implement the goal of a 100% renewable energy system in 2050. It is different from other studies since it relies on deep integration of different energy sectors, including the building stock, which leads to lower costs and resource demands.

The literature review included reports and papers on energy systems and 100% renewable energy strategies towards 2050; heating and cooling energy savings and strategies towards 2050; user behaviour and electricity consumption; flexibility, storage and integrated energy production; and energy supply technologies. In total more than 50 papers and reports were reviewed, which can be found in the reference list.

1.3. Structure of the report

The report is split into five main parts. The first part describes the future 100% renewable energy system and how it is likely to function in 2050. In addition, this part introduces an overview of the current and future role of the building stock in the energy system.

The following three parts describe in detail the specific roles in which the building stock will play in the future energy system. These parts are split into the three main perspectives that the building stock will have and they are labelled as A, B, and C. Each of these perspectives are interconnected (as shown in Figure 8), because each is partly dependent upon the other. For example, low temperature district heating in the new energy supply mix is dependent upon heat savings in the building stock.

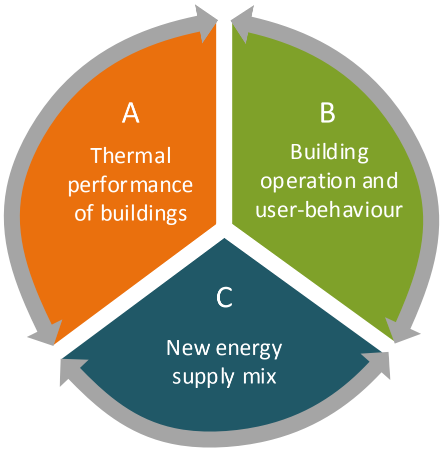


Figure 8: Three perspectives that are key to the role of buildings in future cost-effective sustainable energy systems

Part A focusses on the role of energy efficiency in the buildings and the extent to which thermal energy savings should be implemented to achieve a future smart energy system. Specifically, this part describes the importance of renovating the existing building stock to achieve real change in the thermal energy demand from buildings.

Part B focusses on the operation of the buildings and user behaviour. The importance of coupling renovation initiatives and smart technologies with improved building operation and user behaviour is discussed. This includes an assessment of the contributions and limitations of building flexibility and storage options.

Part C focusses on the role the building stock should have in enabling renewable energy technologies to be integrated into the building stock, and thus into the system. This will be primarily by facilitating the use of low-temperature district heating and energy efficient technologies such as heat pumps.

At the end of each part, the section is summarised by listing the key points and recommendations. These are based on the current role that the building stock has today and how it will need to change in relation to a holistic view of the energy system in the future.

While the main conclusions are presented in the executive summary, the last part provides a brief discussion about the role of the Danish building stock in the future energy system. This discussion will highlight the interconnectivity of the three main roles of the building stock, and the overarching challenges for the role of buildings in an energy system transformation.

2. Buildings in a future sustainable energy system

The aim of this chapter is to provide some background information to help explain the reasons why buildings will form such a key part of an energy system transformation. First, the future energy system is described, in order to illustrate and understand the context in which the buildings will operate. Secondly, the building stock of today is described, in order to describe the benchmark from which the building stock needs to change and to help understand what must be transformed. Lastly, in this chapter, we provide a summary of the main changes for the building stock which will be discussed in greater detail in Part A, B and C.

2.1. Energy system level change

To understand the role of buildings in an energy system, it is necessary to briefly outline the characteristics of the future sustainable energy system. This Smart Energy System[5] concept has been developed at Aalborg University and applied to a variety of countries and contexts. The IDA Energy Vision, which is the point of departure for this report, functions as a model scenario for a 100% renewable Denmark by 2050. The IDA scenario for 2050 is an energy system which is based on a cross-sectoral approach that makes use of synergies between the various energy sub-sectors. The system is cost-effective with a relatively low demand for biomass, which will be an important but increasingly limited resource in the future [9].

The results are based on more than 400 hour-by-hour analyses, balancing all sectors during 8760 hours per year. In the analyses three fuel price levels are combined, with 10 levels of electricity prices to test the robustness of the results in a future European context which is uncertain.

Overall the IDA Energy Vision 2050 shows that:

1) A conversion to 100% renewable energy is a technologically feasible option within economic reach
2) An integrated Smart Energy System design can create a more robust and resilient system, and
3) There is a potential for creating more jobs than in a fossil fuel based energy system as well as lower health related costs from emissions from the energy supply

In Figure 9 the total primary energy supply split into different energy sources is presented. It shows the results for the current energy system, and the system in 2035 and 2050.

[5] For more information, see www.smartenergysystems.eu.

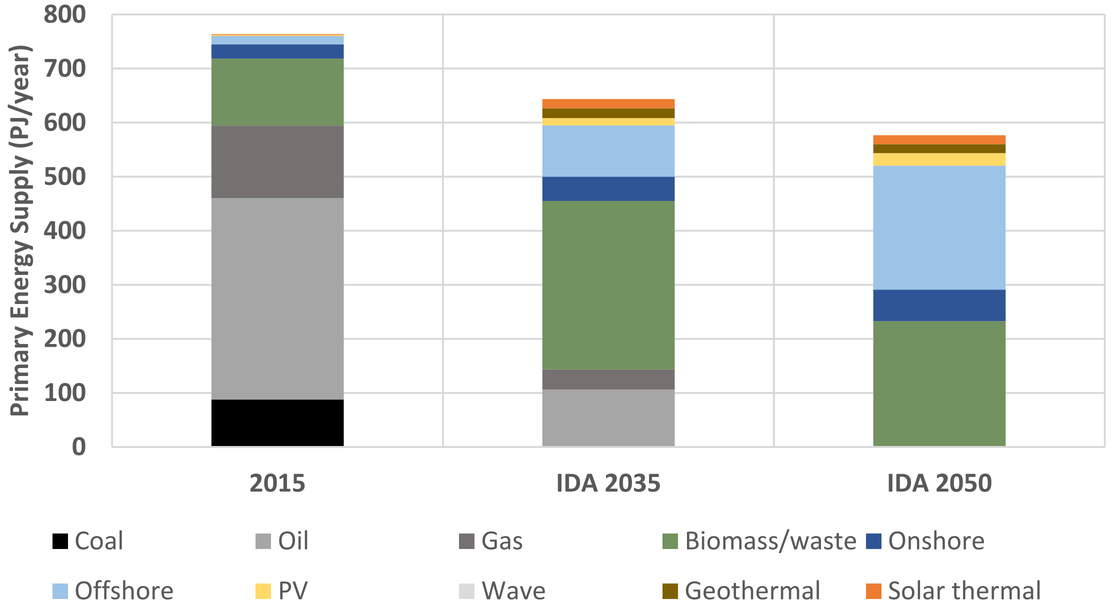


Figure 9: Primary energy supply from different fuel types in the IDA Energy Vision

Electricity from wind power and biomass provides the backbone of the future energy system. The system combines the electricity, thermal, and transport sectors so that the flexibility across these different areas can compensate for the lack of flexibility from fluctuating renewable resources such as wind and solar. This Smart Energy System is built around three grid infrastructures [10]:

Smart Electricity Grids to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and solar power

Smart Thermal Grids (District Heating and Cooling) to connect the electricity and heating sectors. This enables the utilisation of thermal storage for creating additional flexibility and the recycling of heat losses in the energy system

Smart Gas Grids to connect the electricity, heating, and transport sectors. This enables the utilisation of gas storage for creating additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storages can also be utilised

This means the system does not focus on single technologies or sectors but makes effective use of intermittent electricity from e.g. wind turbines and solar panels by integrating the sectors. This increases efficiency and lowers overall energy demand. By utilising numerous technologies such as large-scale heat pumps and electrolysers, system level flexibility is achieved. This type of system leads to a more cost-effective solution, because it uses cheaper energy storage technologies than possible within buildings, as well as balancing savings and renewable energy.

The main changes (in terms of the energy savings, technologies and energy sources) required in the future energy system to create these different types of smart grids and synergies are summarised in Table 1.

Table 1: Changes needed in the energy system from 2015 to 2050 following the IDA Energy Vision

Changes needed in the system	➢ Extensive integration of renewable electricity, predominantly offshore wind
	➢ Complete phase out of fossil fuels
	➢ Savings in building heating and electricity use
	➢ Savings in industry fuel and electricity use
	➢ Increase in DH from 53 % to 66 % of heat supply, with focus on low temperature district heating
	➢ Massive decrease in individual boilers in households
	➢ Massive increase in individual heat pumps
	➢ Substantial increase in EVs
	➢ Extensive increase in the production of electrofuels for heavy-duty transport and aviation
	➢ Robust and resilient energy system with respect to electricity exchange with neighbouring countries and bioenergy prices

In the short run, district heating infrastructure via heat pumps, individual heat pumps and heat storages provides cost-effective flexibility services. In the medium and long run, electrification of transport and production of hydrogen for electrofuels by means of electrolysis can provide cost-effective flexibility services.

In short, the transition of the energy system from a largely fossil-based energy system to a renewable-based energy system will require a high degree of energy savings, a high level of integration between different energy sectors, and a high level of integration of fluctuating renewable energy sources. For this to be achieved, it is essential that the Danish building stock itself must be involved and transform from its current role.

2.2. Buildings today

In order to understand the change in the role of the building stock moving towards the IDA Energy Vision, the current building stock needs to be understood first – in part to provide a benchmark, but also because the majority of the building stock that will exist and operate in 2050 has already been built.

Today the Danish building stock represents an important part of the Danish energy system. It is a major consumer of energy via electricity, heating and cooling. Buildings consume 41% of the total end-use energy demand in Denmark (Figure 10). Due to the poor performance of many buildings in Denmark, currently the Danish building stock has an average heat consumption of approximately 132 kWh/m^2 including hot water (approximately 14 kWh /m^2). These numbers alone show the importance of the building stock on the Danish energy system, and the importance of understanding what can be expected from the building stock in a transition towards a 100% renewable energy system.

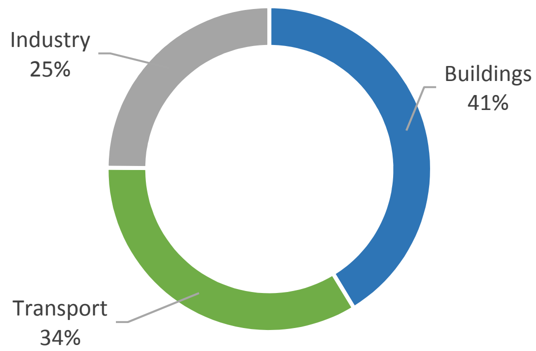


Figure 10: Breakdown of the total end-use energy demand between different sectors in Denmark [1].

In the IDA Energy Vision, the total heated floor space of the current existing building stock for Denmark was around 355 million m^2 [11]. This floor space was used for all calculations for the building stock in the energy system today. The floor space includes residential and office/commercial buildings, which account for the majority of heated floor space in Denmark (86%) (Figure 11). Residential buildings account for the greatest share of heated floor space. The floor space excludes all health, education, hotels, retail and sport buildings, which account for a small share of the total heated floor space in Denmark (14%).

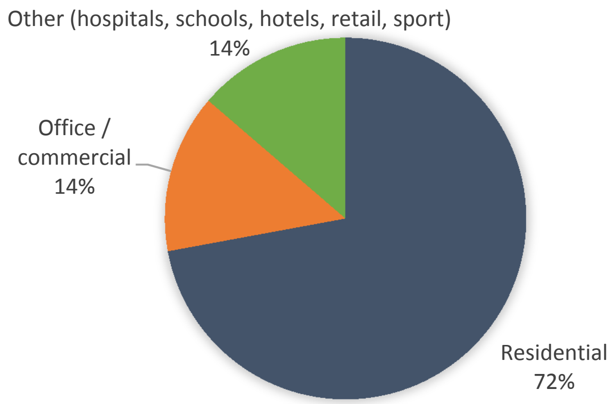


Figure 11: Breakdown of the total current heated floor space in Denmark between residential, commercial/office and other building types (e.g. schools, hospitals etc.)

Improving the technical energy efficiency of the Danish building stock has been part of Danish energy policy since the 1980s, when energy requirements were first included in the national Building Codes [12]. The energy requirements in the national building stock combined with various public subsidy schemes for energy refurbishments have ensured a gradual increase in the technical energy efficiency of the building stock since then (Figure 12).

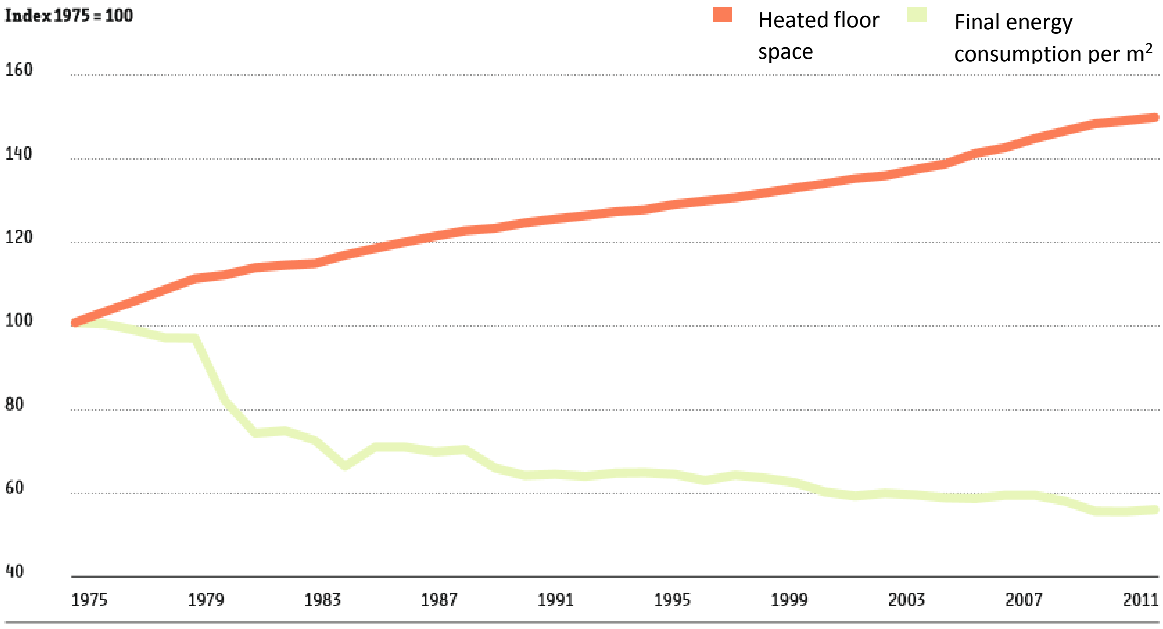


Figure 12: Energy consumption for space and water heating in Danish households [13,14]

The energy consumption per square metre has decreased steadily over the previous 35 years but this has been offset by the growing housing stock, and while savings were initially easy to achieve, the slow rate of improvement over the more recent years demonstrates how difficult it has been to actually decrease the final energy consumption of the building stock.

One of the main challenges in describing and addressing the building stock is the types and uses of the buildings in the stock because different buildings have different energy demands and supplies. In terms of use, most building stock in Denmark is used for residential purposes – as shown in Figure 11 above. Among residential buildings the biggest category by far is single detached houses (1,101,000 dwellings). The second and third largest categories are semi-detached houses (244,000 dwellings) and summer houses (223,000 houses). The residential building stock comprises 91,000 multi-storey buildings [11].

The diversity in the building stock becomes especially clear when looking at the age and performance of different types of buildings. Table 2 below shows the total floor space of different building types and the variations in performance between the buildings. Understanding these differences is useful because it shows which buildings in the building stock are using the most energy, and where improvements should be made [11].

Table 2: Total heated area [m²], including areas from protected buildings and buildings worth preserving that have heat installations (data from BBR 2012), and calculated current unit consumption (kWh/m²) of the building types and construction periods [11]

Period	Unit	Cottage	Single-family dwelling	Terraced /link detached house	Flat	Office/ commercial	Total
Before 1890	m²	7,232,815	11,082,993	1,575,126	6,252,303	3,920,304	**30,063,541**
	kWh/m²	184	170	158	151	130	
1890-1930	m²	8,833,785	26,433,186	2,338,394	20,773,880	6,915,883	**65,295,128**
	kWh/m²	171	165	158	154	125	
1931-1950	m²	2,150,271	16,151,211	1,892,749	15,051,075	3,099,172	**38,344,478**
	kWh/m²	162	164	149	157	129	
1951-1960	m²	737,804	12,769,063	2,191,133	8,012,426	2,902,902	**26,613,328**
	kWh/m²	151	155	143	148	127	
1961-1972	m²	787,751	38,567,879	4,653,503	14,202,116	10,525,416	**68,736,665**
	kWh/m²	136	134	120	132	118	
1973-1978	m²	632,889	22,152,767	3,764,218	4,495,472	5,741,957	**36,787,303**
	kWh/m²	117	120	113	121	120	
1979-1998	m²	967,513	17,801,805	12,908,011	7,931,108	14,140,062	**53,748,499**
	kWh/m²	100	105	97	109	103	
1999-2006	m²	459,339	7,386,259	4,091,722	3,822,652	6,625,526	**22,385,498**
	kWh/m²	81	84	82	84	90	
After 2006	m²	418,239	5,068,685	1,986,454	2,414,296	4,809,281	**14,696,955**
	kWh/m²	67	67	66	61	83	
Total	m²	**22,220,406**	**157,413,848**	**35,401,310**	**82,955,328**	**58,680,503**	**356,671,395**

In Table 2 several points about the current building stock become clear. Firstly, the majority of the building stock was constructed before the 1970s. This is because the buildings have long material and building lifetimes, therefore they are not replaced often [15]. This is unlikely to change; between now and 2050 the demolition rate is only around 0.25% per year so most new buildings are an addition to the building stock, as opposed to phasing out older buildings [16]. This means that the building stock in 2050 will include nearly all (approximately 90%) of the buildings that make up the stock today [17].

Secondly, the performance of older buildings is significantly lower than those built more recently, especially after 1970. Buildings of the same type that were built between 1890 and 1930 – the most prevalent category in terms of area - use up to 4 times as much energy per square metre compared with those built more recently. Only after the 1980s did the building energy standards require a better performance. However, despite the stricter standards, only in the last few years have new buildings reached a point where energy performance is sufficient [11]. This means there is a large potential to achieve space heating savings in the current building stock which has been shown in numerous studies [18–21].

The importance of improving the performance of existing buildings is also clear when the total demand from different building periods is considered. Based on data from SBi for building types, ages and specific heat demand (kWh/m²), the total heat demand in the different building types from different construction periods is shown in Figure 13 [11]. As shown, most heat demand is from older detached houses and apartment buildings from before 1980; this is then also where the largest potential for savings per square metre can be found.

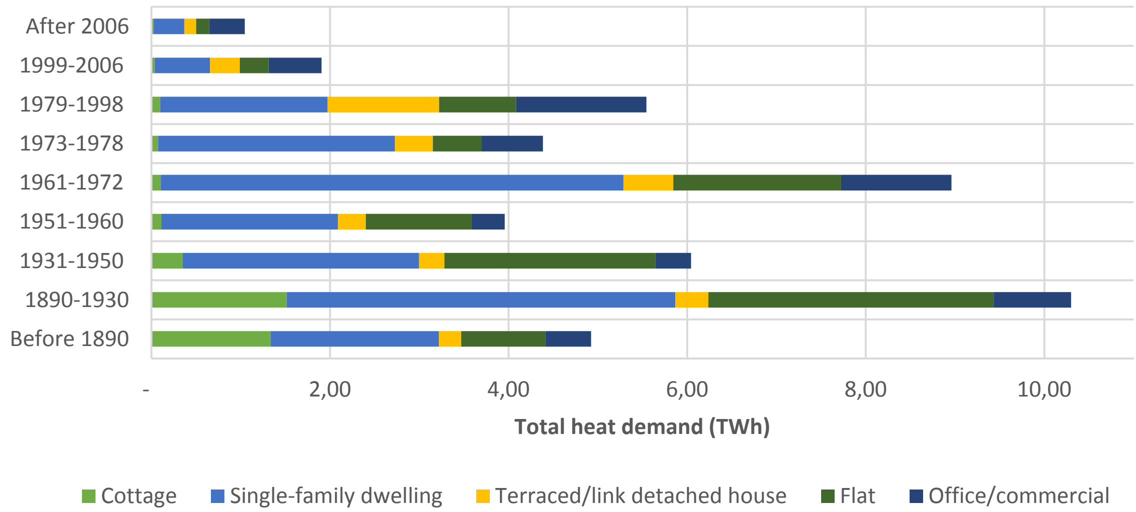


Figure 13: Total heat demand for different building types built in different periods

2.3. Buildings tomorrow

To achieve the IDA Energy Vision, several changes in the role and function of the building stock are required compared to the current state. As the energy system transforms, there are changes both in the amount of energy that is demanded, and the technologies used to provide the energy.

There are three broad perspectives on the roles that the building stock will have in the energy system transformation (see Figure 14). Most are prerequisite or contingent to developments in other sectors of the future energy system, so there is a real need for the building stock to address these perspectives. If not the implementation of some key renewable energy infrastructures required for the 100% renewable energy system may not be achievable - which will increase the overall costs of the transformation.

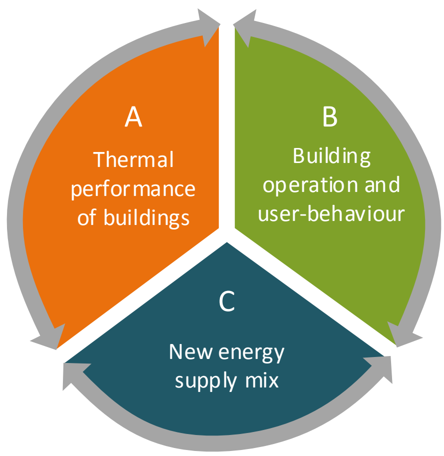


Figure 14: Three perspectives are key to the role of buildings in future cost-effective sustainable energy systems

The roles of the building stock in these three areas are all deeply interconnected, to the point that one is likely impossible without the other and in most cases parallel developments are required. Each of the three key areas are briefly described below before going into more detail in Parts A, B, and C. The key changes in the role of the building stock for each area are also summarised in Figure 16 below.

A. Thermal performance of buildings: reducing the system energy demand through improved thermal energy efficiency from renovations

The building stock as a whole, and especially existing buildings, needs to become more efficient if it is to enable a cost-effective, renewable, and flexible energy system.

The IDA Energy Vision investigated the cost-optimal level of heat savings in existing and new buildings in the context of the 100% renewable energy system in Denmark in 2050, placing the buildings within context of the entire system and not on an individual building basis. It showed that existing buildings must reduce their total heating energy consumption by approximately 40% between today and 2050. In Figure 15 below the overall change in the heating performance of the building stock from 2015 to 2050 is illustrated. This shows, for existing and new buildings and the entire building stock, the total heated floor space, the average performance per square metre and the total heating demand.

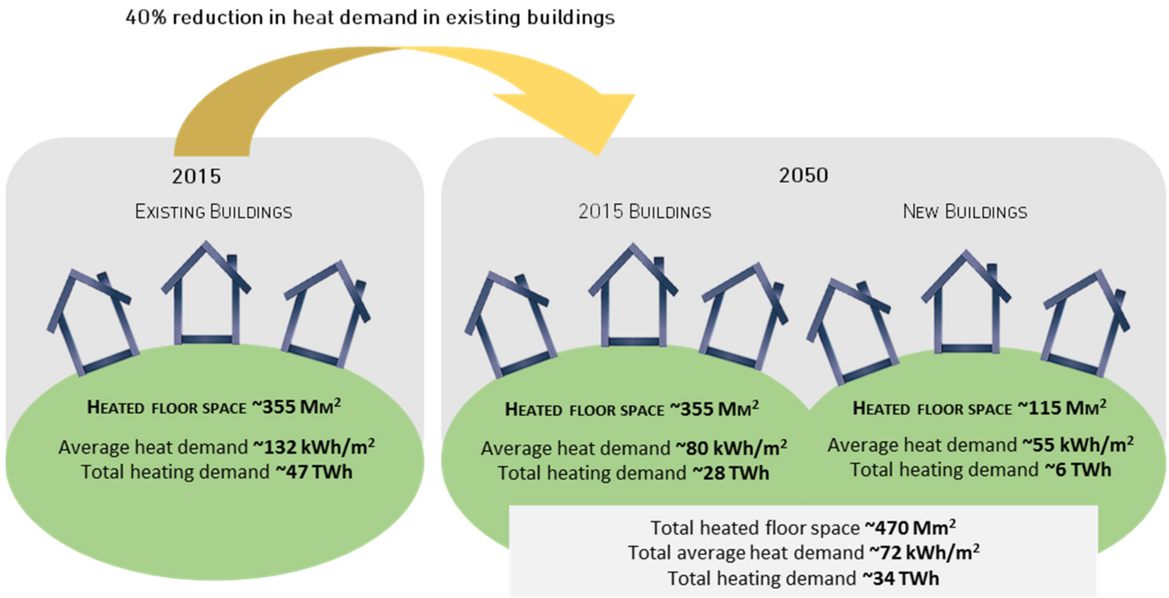


Figure 15: Growth of the Danish building stock floor space from 2015 to 2050, including average heat demand per square metre, and total heat demand

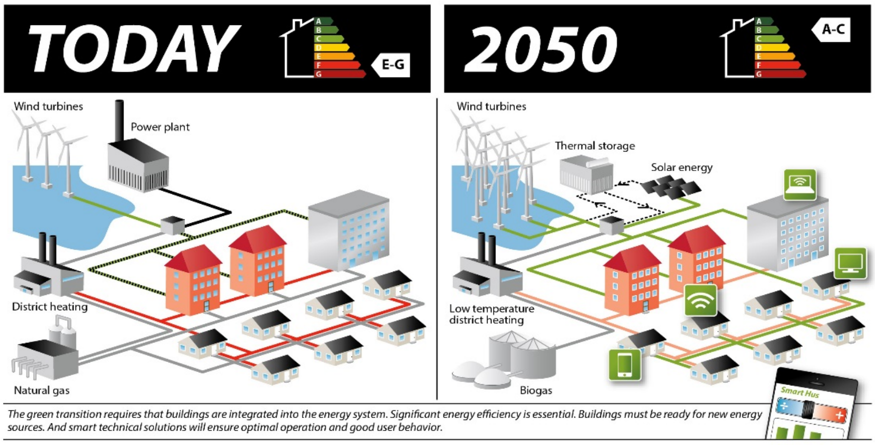
B. Changing the operation of the buildings and user behaviour to ensure heating and electricity savings are achieved

The operation and user behaviour of people in buildings is a crucial element to achieve savings in heating, cooling and electricity demands, along with more efficient technologies and appliances.

Additionally, the operation of buildings is often linked to flexibility, although many building-integrated technologies are unlikely to be cost-effective for the integration of renewable energy in a Smart Energy System. Several of these technologies are discussed and assessed from a system perspective.

C. Enabling new energy supply technologies and infrastructures such as low-temperature district heating and heat pumps

Understanding the energy supply side technologies for buildings is crucial for making effective decisions on energy use in buildings. In the IDA Energy Vision these infrastructures represent the link between the thermal and electricity sectors that underpin the Smart Energy System, and the system flexibility. It was important to determine the level of district heating and the cost of supplying heat to the buildings since this helped to determine the level of savings required in the building stock. In Varmeplan Danmark (Heat Plan Denmark), an underpinning report used in the IDA Energy Vision, an expansion of district heating, which should move to lower temperatures, is suggested, in combination with an increased use of heat pumps. Electricity is supplied mainly via fluctuating renewable energy sources; primarily offshore wind power.



Thermal performance of buildings	Level of heat demand in existing buildings	Low, medium and high	Low
	Level of heat demand in new buildings	Very low	Very low
Building operation and user behaviour	Level of appliance electricity demand	Medium	Low
	Level of heat pump electricity demand	Low	Medium
	Energy-efficient user practices	Limited	Medium
	Building level flexible demand	None	Very limited
	On-site electricity production and own-use	Very limited	Very limited
	On-site electricity storage	None	Very limited
New energy supply mix	Level of district heating coverage	High	Very high
	Low temperature district heating	None	High
	Large scale heat pumps	Low	High
	Individual heat pumps	Low	High
	Individual boilers	High	Low

Figure 16: Illustration of the Danish building stock in the energy system in 2015 and 2050 with a list of the three key areas in which the Danish building stock will be more involved in the future energy system

Background of the IDA Energy Vision 2050

This report has been prepared by the Sustainable Energy Planning Research Group from Aalborg University. The IDA Energy Vision 2050 and the present report about Future Green buildings builds on previous research on the dynamics between renewable energy systems and the built environment. These include:

- *The IDA Energy Plan 2030* — *2006*
- *Heat Plan Denmark* — *2008 & 2010*
- *The IDA Climate Plan 2050* — *2009*
- *Coherent Energy and Environmental System Analysis (CEESA)* — *2011*
- *Heat Saving Strategies in Sustainable Smart Energy Systems (NZEB)* — *2014*
- *The IDA Energy Vision 2050* — *2015*

The **IDA Energy Plan 2030** was the first study to do detailed system designs and energy balances for 50% renewable energy in 2030 and include a target year and draft proposal for 100% renewable energy in 2050. The study includes the first systematic analyses of the level of heat savings compared to district heating or individual heating options [3].

The two **Heat Plan Denmark** studies went into detail answering the questions on how heating could be provided in various future renewable energy system configurations. The Heat Plan Denmark studies reached the conclusion that a feasible option could be to expand district heating from 46% in 2006 to somewhere between 63% and 70% of the total net heating demand. The remaining buildings should use solutions based on individual ground-source heat pumps and solar thermal. The reports investigated all heating technologies from boilers, micro-CHP and electric heating to heat pumps (air to air or ground-source). The reports used GIS and energy system analyses together with different heat saving level to investigate the options [25,49].

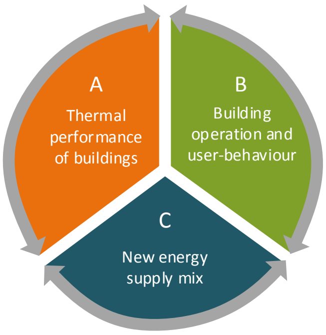
The **IDA Climate Plan 2050** has a systematic focus on 100% renewable energy in 2050 and intermediate years in 2020 and 2030. The study included additional transport analyses and biomass assessments, as well as an estimate of health costs and job creation. It included contributions from the first Heat Plan Denmark study, as well as preliminary results from the CEESA (Coherent Energy and Environmental Systems Analysis) study [2].

As in the IDA plans, the aim of the **CEESA** scenarios was to design a 100% renewable energy system by the year 2050, however heavy focus was put on the re-design and Smart Energy Systems. Specific focus was put on fuels for transport in the light of the biomass resources available [5].

In **Heat Saving Strategies in Sustainable Smart Energy Systems** the aim was to investigate in more detail the level of heat savings in existing and new buildings compared to renewable heat production. The results were used in the light of nearly Zero Energy Buildings (nZEBs) and assessed the energy consumptoin per square meter in new and existing buildings in a renewable ernergy system context [21].

The aim in the **IDA Energy Vision** was to show that it is possible to create a cost-effective energy system for the future only based on renewable energy sources, which is also robust towards changes in fuel and electricity prices. For this, a long-term perspective was used towards 2050 with an intermediate scenario for the year 2035. The scenarios included the latest knowledge in smart energy systems and on electrofuels for transport. [1].

A. Thermal performance of buildings



	Today	Future (2050)
Level of heat demand in existing buildings	Low, medium and high	Low
Level of heat demand in new buildings	Very low	Very low

A.1 Cost-efficient energy savings

The most important contribution the building stock will make to the future energy system is through improved energy efficiency and energy savings, reducing the consumption of heating, cooling and electricity. Numerous studies have investigated the potential and need to save heat in the building stock in Denmark for the future, and large potential savings have been identified [18–21].

In the IDA Energy Vision, the level of heat savings was determined for existing and new buildings from 2015 to 2050 by comparing the cost to renovate the buildings against the cost of supplying heat. At a certain point during the renovations of buildings and improving the energy efficiency, the system level cost of further renovations is more expensive than the cost of supplying heat to the buildings (Figure 17) [21]. Energy saving strategies should therefore be preferred as long as the marginal cost of realising these energy savings are lower than the marginal cost of increasing the production of energy by means of renewables. Thus at this point, renovations should cease and heat should be supplied.

Optimal energy saving strategies

Based on the optimal level of district heating and the breakdown of heat supply technologies in the remaining buildings as determined in the IDA Energy Vision, the cost of supplying heat could be determined. This allowed for the optimal level of savings to be identified, based on the premise that energy saving strategies should be preferred as long as the marginal cost of realising these energy savings is lower than the marginal cost of increasing the renewable production. This is demonstrated in Figure 17 below. Note that these calculations should be seen as an appropriate magnitude of savings as opposed to an exact target. In light of previous achievements to reduce heat demand in buildings, these saving levels will be ambitious since this level of savings have never been achieved in previous years.

Energy savings from improved building performance

Energy savings on the system level are extremely important because (a) they reduce the overall need for energy (b) they reduce peak-demand, and thereby reduce the demand for marginal production facilities (c) a better balance is obtained between the energy needed during summer and winter, because a larger proportion is from (seasonally more stable) hot water use and (d) they allow for lower temperatures in the district heating system, solar thermal supply or heat pump technology, which increases efficiency and allows for integration of renewables.

In the IDA Energy Vision, the overall building stock space heat and hot water performance was calculated at approximately 132 kWh/m^2 in 2015 [1]. This takes into account all residential and commercial/office buildings but excludes buildings for health, education, hotels, retail, and sport.

Figure 17 shows the marginal cost of providing heat (orange line) and the marginal cost of reducing heat demands in new and existing buildings (black and red lines respectively). As the performance of buildings increases (and average heat demand in kWh/m^2 falls), the marginal cost of providing heat falls. This is in part because the capacity of the systems can be re-dimensioned, and in part because a much higher level of efficiency can be gained as energy savings measures allow for lower temperature heating. These developments are further discussed in Part C.

The marginal cost of reducing heat demand rises as more heat savings are implemented. This is because after cheaper and simpler renovation measures have been implemented (such as upgrading windows, walls and roofs), further renovations and reducing the specific heat demand (kWh/m^2) becomes substantially more difficult to integrate with the already existing building structures, and thus expensive. At this point, the cost of providing heat is less expensive than further savings, which represents the optimal level of savings in the building stock. In new buildings, energy saving solutions can be installed easily and at a cheaper cost, meaning the marginal costs are lower. However, as the new buildings become increasingly energy efficient the marginal costs to save heat demand increase rapidly, resulting in a point where the cost of supplying heat is lower than making further energy saving measures.

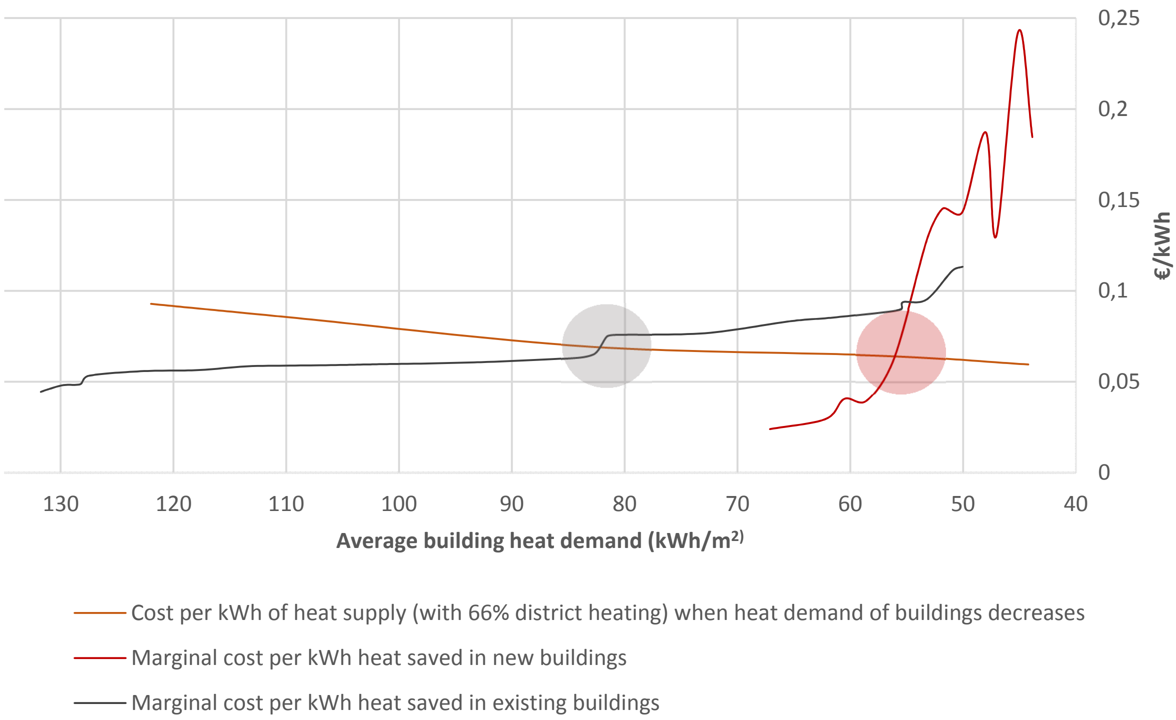


Figure 17: Marginal costs for reducing heat demand in existing and new buildings compared to marginal costs of providing more energy in the CEESA 2050 energy system [21]

Figure 17 shows that for existing buildings the heat demand per square metre should reduce from the current 132 kWh/m^2 to approximately 80 kWh/m^2 (grey circle), which represents about a 40% reduction. Note that the improvement of heat performance in existing buildings takes into account the energy demand of the entire building stock including the additional energy demand of the buildings constructed between today and 2050. This means that even as new energy efficient buildings are built (approximately 25%-30% increase in floor space is expected from today to 2050), the heat energy performance of the existing buildings should still be reduced by 40%. After this point the cost of further savings is more expensive than supplying heat (orange line) to the buildings. For new buildings, the cost-effective level of heat demand is likely to be in the red circle (approximately 55 kWh/m^2) since after this point the cost of further improvements of the heat demand in the building are more costly than supplying heat.

A.2 Savings in new buildings

Heat savings required in new buildings are very different than for existing buildings. New buildings have attracted a lot of focus in the endeavour to save energy in the Danish building stock. However, new buildings built from today to 2050 will not proportionally represent a large part of the building stock, and be responsible for a disproportionately small amount of the energy required for buildings in 2050. Therefore, a strategy for increasing the energy efficiency of the building stock that focuses primarily on new build housing would have marginal effects, even with a time horizon of 35 years. Despite this, the newly built buildings should be built with good energy performance from today to 2050 to prevent new buildings from becoming large users of energy. Fortunately, this is already the case under the current Building Code.

In the IDA Energy Vision, if further improvements in heat performance are invested in new buildings leading to a better building energy performance, this would lead to higher overall system costs, as shown in Figure 18 below. Thus it is recommended that the level of heat performance in the IDA Energy Vision is targeted for new buildings.

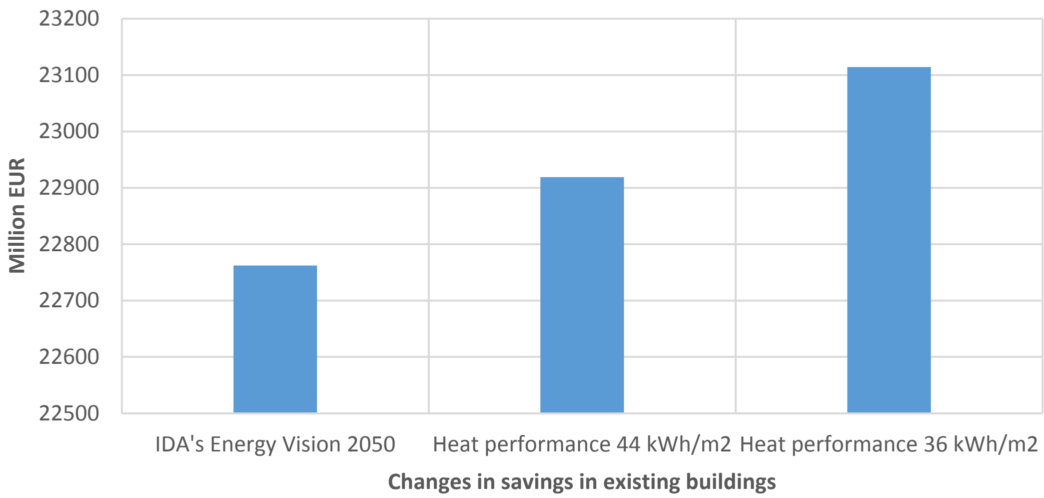


Figure 18: Total annual costs (million €) in the IDA Energy Vision compared with two alternative scenarios 1) new buildings' heat performance is improved to 44kWh/m^2 and 2) new buildings' heat performance is improved to 36kWh/m^2

In the Danish Building Code (BR15), energy frames after 2020 are defined for new residential and non-residential buildings for the net primary energy demand. For residential buildings and non-residential buildings these energy frames are 20 kWh/m^2/year and 25 kWh/m^2/year, respectively [22]. Based on the IDA Energy Vison recommendation for the heat consumption of new buildings, which is approximately 55kWh/m^2/year as described above, it appears that this requirement for new residential and non-residential buildings is unnecessarily high. This is because for the future energy system most energy savings need to be achieved in the existing building stock as opposed to the new stock, since more energy savings can be achieved this way, at a lower cost.

In order to achieve the strict BR15 energy levels it is permissible to install energy production units on-site or nearby the buildings, for example solar PV in combination with a battery. However, this is not a recommended solution in the context of the energy system [23,24].

The risk of promoting batteries on the household level is high - which is problematic if careful consideration is not put into regulation of PV, electricity levies and the buildings codes. Installing energy production units on new buildings happens in response to strict building standards and it allows for sending surplus energy from these units to the grid, which counteracts some of the buildings' energy consumption. This could lead to less energy savings in the buildings than what is feasible and necessary. These strict energy levels for new buildings ignore that in order to have a meaningful impact on the system energy, energy need to be saved in the building stock. From a system perspective, producing more energy in response to consumption is not an actual saving; rather, it is a compensation.

In order to achieve the appropriate level of energy savings, for the renovation of existing buildings and new buildings the demands for the building insulation level and the installation of solar thermal or PV should not be mixed in the regulatory and policy framework.

A.3 Energy saving renovations in existing buildings

A recent study from 2016 from SBi calculated how the total heat consumption of the built environment is expected to decrease for existing buildings in the coming decades, due to tighter energy requirements in the Building Codes [11]. The study shows that from 2012 to 2050, in the best case scenario, with full compliance with the Building Code, the heat demand would be reduced by around 30% (just under 1% per year) compared with the heat demand in 2012. Even in a best case scenario this does not meet the requirement as found in IDA Energy Vision 2050 (40% minimum, as shown above for existing buildings) which would require a reduction of energy consumption of around 1.15% per square metre per year for the existing building stock to 2050.

Historical and projected trends

In the past 35 years the heat demand per square metre of the building stock has decreased steadily as shown in the index in Figure 19 (grey line from 1980-2015). Meanwhile, the building floor space (blue line) has increased.

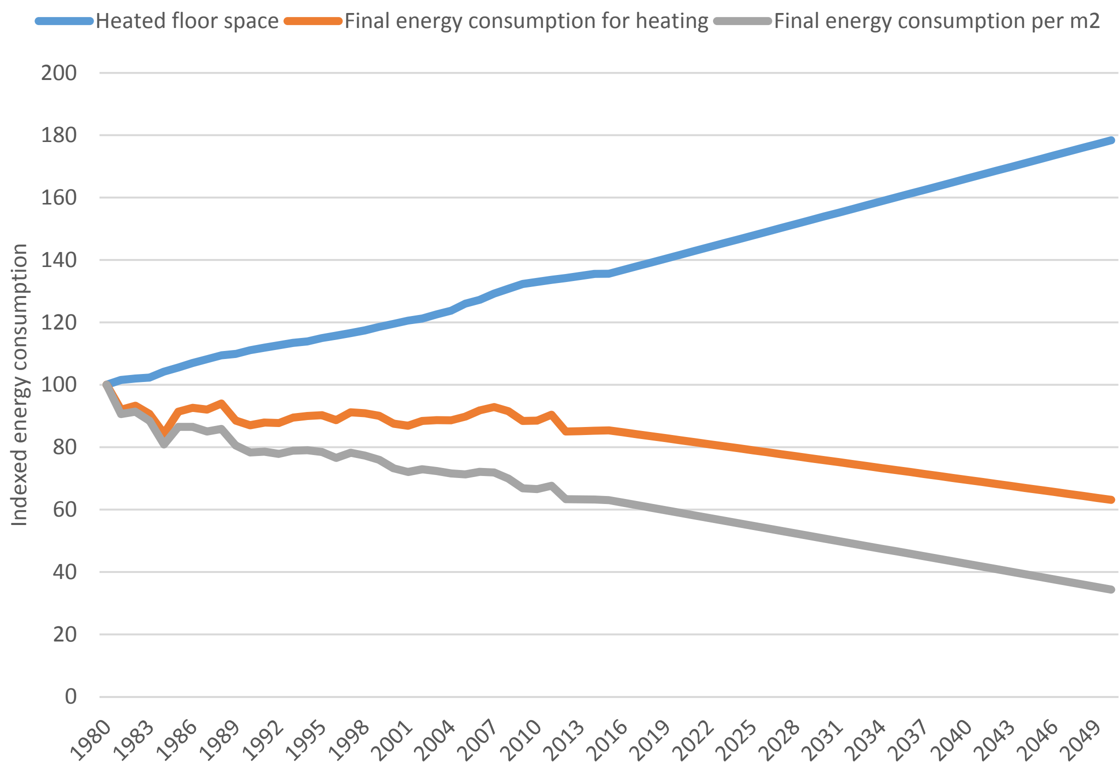


Figure 20: Indexed energy consumption for space and water heating in Danish buildings from 1980 to 2015 [25,26] *and projected to 2050 [1]. Index 1980 equals 100.*

In the future energy system, the energy savings target in 2050 must be met in order to ensure that the renewable energy system can be achieved, even with growing floor space in Denmark. Energy savings in the existing building stock will to some extent be achieved due to the energy requirements in the Building Code but there must also be an acceleration of renovations in the existing building stock to ensure that the energy savings are achieved from today to 2050. This acceleration will ensure that the overall final energy consumption actually decreases from today to 2050, even with additional floor space from new buildings.

Gram-Hanssen concludes that there needs to be new innovative policy measures to cope with the realities of energy renovations of owner-occupied houses. Policy measures include building regulations, energy taxes as well as different types of incentives and campaigns [27].

In the IDA Energy Vision, a sensitivity analysis was done to show the impact of having different heat saving levels. Figure 21 shows that when there are more or less savings in heat demand, the cost to the system increases. The total heat energy demand reduction of around 40% (including hot water) In existing buildings leads to the least-cost energy system. In addition, with less heat savings the amount of primary energy demand increases (Figure 22).

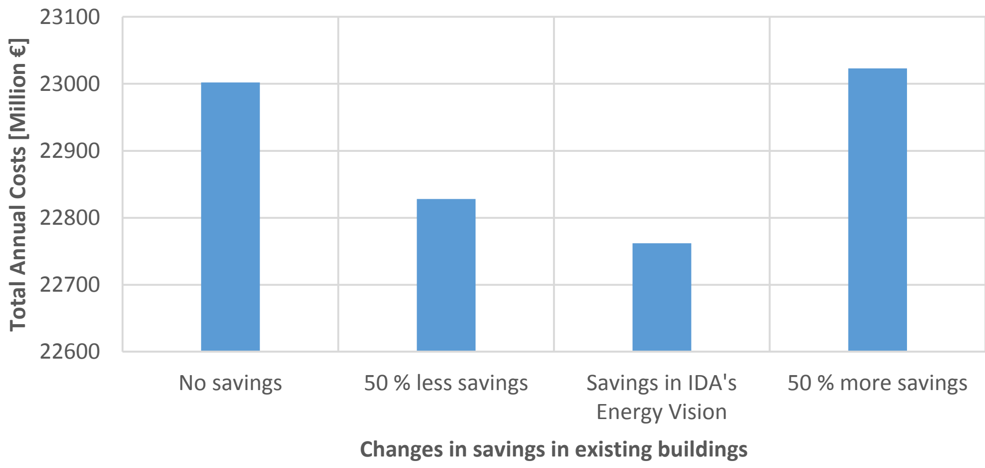


Figure 21: Total annual costs in the IDA Energy Vision and in three alternative scenarios 1) no heat savings in the existing building stock 2) 50% less heat savings in the existing building stock 3) 50% more heat savings in the existing building stock

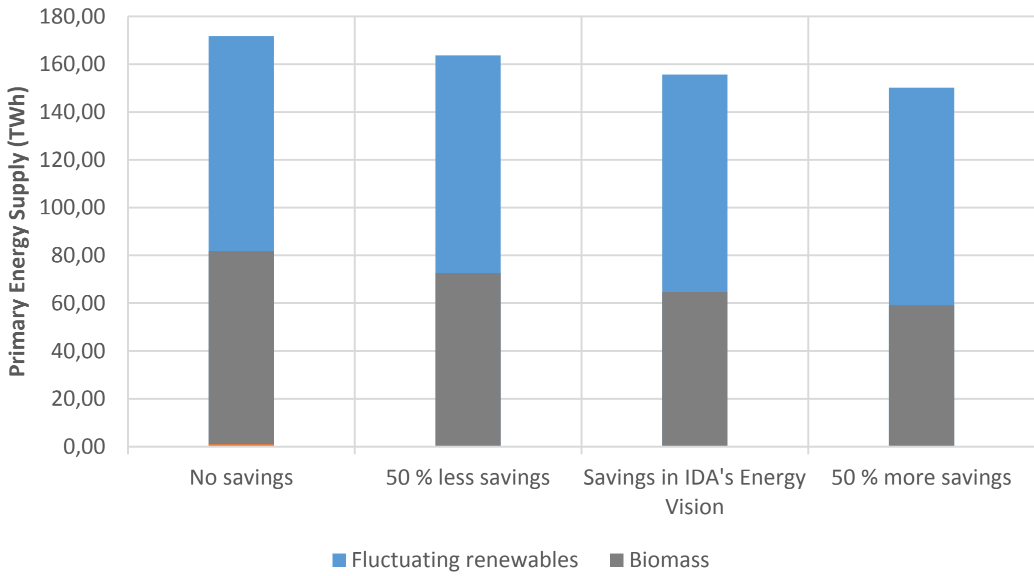


Figure 22: Total primary energy supply from renewable energy and biomass in the IDA Energy Vision and in three alternative scenarios 1) no heat savings in the existing building stock 2) 50% less heat savings in the existing building stock 3) 50% more heat savings in the existing building stock

If there are less or no savings the amount of biomass that will be required in the energy system will be much higher, as seen in Figure 22. This additional biomass is more than what Denmark will have available (200-240 PJ [5]) and therefore Denmark would need to invest more in alternative ways of providing energy to the system, for example in the form of more wind turbines, thus increasing the cost of the system further.

An assessment has not been made on which existing buildings should be renovated first and on how many should be renovated per year, as these analyses are still ongoing. However, in general, bulk energy renovations that deliver the most cost effective energy savings should be prioritised, which means focusing on the least cost renovations in the proportion of the existing building stock that has the greatest heat demand. Based on this principle, older buildings, particularly individual detached houses, should be renovated first and buildings younger than 1980 should be placed in a lower priority for new renovations.

Energy renovation during general renovation

An important point to realise is that all these cost calculations are made based on the assumption that energy refurbishments of buildings are combined with general refurbishment activities when buildings are being renovated anyway. In other words, energy savings measures should only be undertaken in conjunction with general renovations. Otherwise, energy saving measures are unlikely to be cost-effective: calculations from SBi suggest that the cost of achieving energy reduction by means of energy refurbishment are reduced by approximately 45% when energy refurbishments are carried out in combination with general refurbishment activities [28]. Since the frequency of general refurbishment activities is 20-50 years, depending on the part of the building, it is critical that energy efficiency is systematically addressed in relation to all refurbishment activities between now and 2050. Otherwise, either the cost of implementing energy savings is excessive or the level of savings necessary for a 100% renewable energy system will not be achieved.

Based on the expected lifetime of building materials in Denmark the general refurbishment needs for different parts of the buildings have been analysed (Table 3), to understand what level of energy renovation can be anticipated [11].

Table 3: General refurbishment need until 2050 for different parts of buildings based on expected lifetime of building material

	Share of renovated area, exterior walls	Share of renovated area, roof	Share of renovated area, windows
2035	11%	60%	95%
2050	18%	82%	150%

The analysis illustrates that even if all general renovations are combined with energy saving measures, most of the exterior wall area (82%) and a considerable part of the roof area (18%) will not be energy renovated, because there is no need for general refurbishments between now and then. The same analysis shows that there is significant increase in the amount of general renovations of roofs until 2030; after 2030 renovations of roofs begin to decrease. The same trend is to a lesser extent visible in relation to renovations of exterior walls where renovation activities decrease slightly after 2020. Both these trends emphasise the need to take advantage of renovations that happen now, in order to be able to achieve the necessary energy efficiency by 2050.

A.4 Key points and recommendations

- In the future, the same as today, buildings will be responsible for a large proportion of heating, cooling and electricity demand in the energy system. However, in the future, the energy system must consume less to achieve the 100% renewable goal, meaning that it is **essential that the building stock is part of the energy transition** through energy savings. Overall existing buildings should reduce their total space heating energy consumption by around 40% between today and 2050 (including hot water). The total electricity demand from the building stock should remain at the same level as today, even with more buildings and electric heat pumps. This means electricity savings should still be promoted in new appliances. Energy efficiency and energy savings in the building stock will lower the total amount of energy required, increase retention of heat in the building envelope, lower the peak energy demand levels, and lower the temperature level required from heat supply technologies. This is very important for the overall performance of the system.

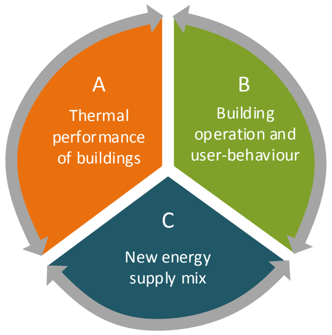
- Between 1-1.5% of the building stock is newly built yearly. Most of these buildings represent a growth in the building stock rather than replacement, which is only around 0.25% per year. In total it is expected that new building floor space will increase by around 25-30% from today until 2050. The buildings built today are required to be highly energy efficient according to the BR15. This means that for the building stock as such, **it is less important to place focus on new buildings to save energy in the future energy system**, since very little renovation activities will need to be done until 2050 for these buildings.

- Around 90% of the building stock existing today will exist in 2050. Therefore, **energy savings need to be made in the existing building stock**. To have a cost-effective energy system it is a prerequisite that existing buildings reduce total heating energy consumption by around 40% between today and 2050. This means the average heat demand per square metre for the existing building stock should be reduced by around 1.5% per year until 2050. In the last 15-20 years the average heat demand per square metre has been decreasing at around 0.8-1% per year. This means that an increase in renovation rates for existing buildings is necessary. If this is not achieved by 2050, the need for biomass may exceed the available biomass in Denmark or more wind turbines and PV may be required. This will eventually lead to risks related to energy security of supply and certainly higher costs of the energy system.

- **Renovations should be targeted at the worst performing buildings first.** A detailed list of buildings to be renovated has not been provided in this report. However, based on this assertion, most renovation activities in existing buildings should be done in buildings built prior to 1980, especially for older buildings such as individual detached houses built in the early 20th century.

- There is a very specific and limited window of opportunity to implement energy renovations in existing buildings. It is essential that **energy renovations are done when renovations are already being carried out** on specific parts of the building, for example, roofs and windows. This is because it is not cost-effective to do energy renovations by themselves. Certain policy measures would likely be needed to encourage this activity.

B. Building operation and user behaviour



	Today	Future (2050)
Level of appliance electricity demand	Medium	Low
Level of heat pump electricity demand	Low	Medium
Energy-efficient user practices	Limited	Medium
Building level flexible demand	None	Very limited
On-site electricity production and own-use	Very limited	Very limited
On-site electricity storage	None	Very limited

The operation of a building and the users' behaviour in the building has a large influence on how the building performs within the energy system. For the building stock to contribute towards the energy system, there are two important developments that should guide building operation and user behaviour:

1) The operation should be according to the needs of the energy system and not the individual building. This ensures that decisions are made on a cost-effective basis for the system, which is particularly related to increasing flexibility in the system.

2) Because savings of both heating and electricity are so important, involving users and addressing their behaviours, e.g. habits, norms and knowledge must be part of the effort to make the system more effective.

With this in mind, firstly the operation of the buildings according to the needs of the system is discussed, followed by the options that have been explored on the building level to operate the buildings and change user-behaviour.

B.1 Operating buildings according to the needs of the future energy system

Today, fossil fuels provide flexibility in the system since they store energy which can be utilised at any time. This means that flexibility is sourced from the energy supply side. In the future energy system, as fossil fuels are phased out, and since most renewable energy sources fluctuate, the system will shift towards deriving flexibility from the demand side. There are two methods of achieving this 1) through flexible demand in buildings and industry and 2) through system level flexibility.

Energy storage and flexible demands

System level flexibility is focussed on utilising the entire energy system for flexibility via large-scale energy storage and technology switching. In the IDA Energy Vision, the aim was to find the least-cost energy system, therefore the flexibility in the system was designed to use the least expensive storage technologies based on these costs. Ideally, the least-cost technologies are used first followed by more expensive technologies. From this, it is clear that linking the different sectors in the energy system and exploiting the synergies creates is a far cheaper and more effective way of creating flexibility than trying to create flexibility at the building level. For example, using large-scale heat pumps to provide district heating, especially in combination with thermal storages, can be much more cost-effective due to economies of scale. Figure 23 demonstrates the investment cost (logarithmic scale) and efficiency for storing the different forms of energy, including electricity storage. As shown, electricity storage is the most expensive, followed by thermal, gas and liquid fuel storage. Electricity storage also has the lowest energy efficiency.

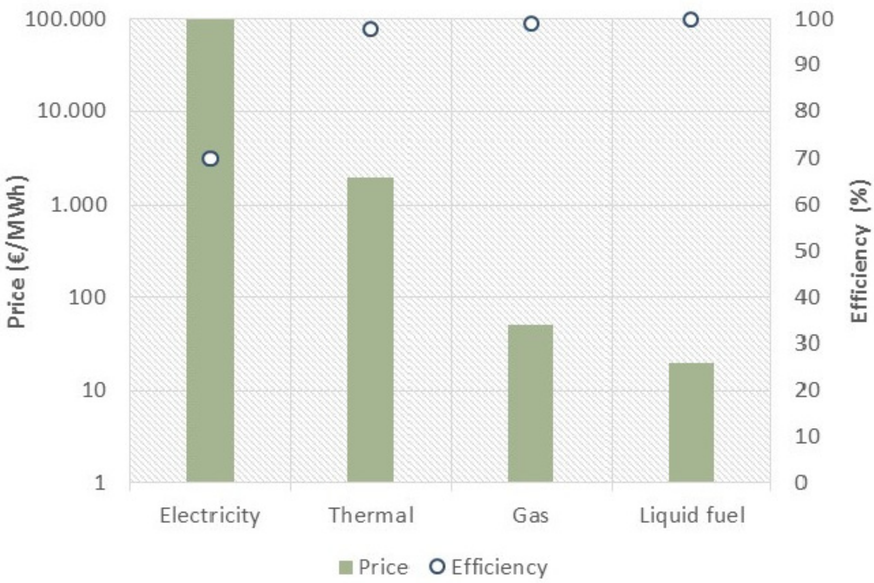


Figure 23: Investment costs and efficiency comparison for different energy storage technologies

Based on these and other cost data, when selecting the best solutions for the future energy system in the IDA Energy Vision based on the modelling, it was demonstrated that the building stock should have a limited role in providing flexibility services since this can be better cost-effectively delivered elsewhere via system flexibility (Figure 24). Due to economies of scale, individual storage is more expensive than larger scale storage. For example, the cost of investing and operating one big battery of 10,000 kWh in the system level is substantially lower than operating a thousand 10 kWh batteries installed in buildings since big batteries can use new technologies. This is the same for other energy storage technologies as well. In addition, compared with system level storage the energy storage capacity of buildings (electric batteries, hot water) is difficult, and it is expensive to translate this storage capacity into beneficial flexibility services [5,29].

As shown in Figure 24, the majority of the conventional electricity demand in the system remains the same because it does not need to be made flexible. It simply follows the traditional load profile from today. This means that in the future system with more renewable energy the buildings are still able to consume the electricity in normal hours like today but the consumption per day will be lower due to improved energy efficiency and energy savings.

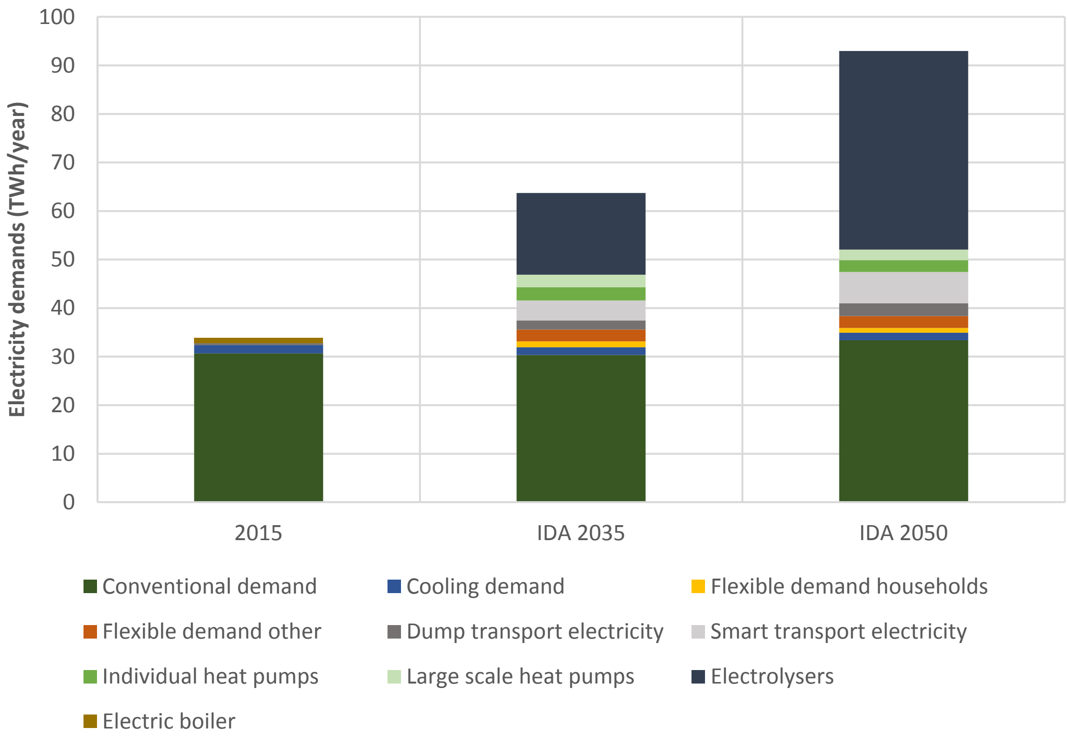


Figure 24: Electricity demand of different end-users

To enable the most cost-effective energy system, the flexible demand in households, services and industry should be minimal. Some flexible demand in households (in yellow) would likely be for programmable appliances such as dishwashers, washing machines, heat pumps, etc. and could be flexible over one day or a week [1]. However, building level flexible end-use patterns in response to price signals in the electricity market in homes can be an expensive and inefficient way of providing flexibility services [30]. Studies show that even this amount of flexibility may still be too expensive and inconvenient to make it worthwhile [30].

Individual heat pumps, which can provide flexibility within buildings, are emphasised in Figure 24 above. Heat pumps should be operated in a way that they consume electricity when the system needs them to, but this should be done in buildings with good energy efficiency and heat retention so that the building envelope can provide the storage of the heat for when it is required. Heat stored in a heat accumulation tank on the building level is more expensive in comparison to heat retention [29]. This emphasises even further the importance of renovating buildings so that they are energy efficient buildings and can retain heat.

On the demand side, some flexibility can come from district heating, and some system level gains can come from shifting heat demands. This however is hard for an individual consumer to control as, for example, it may be counterintuitive to not shut down the heat in the night time. Smart meters could enable utilities and consumers to collaborate in these situations for optimal operations.

Large scale heat pumps, electric vehicles and electrolysers can play a significant role in 2035 and 2050, and can utilise cheaper storage options than heat or electricity storage at the building level.

Near Zero Energy Buildings

By operating the buildings according to the needs of the energy system, this means that near Zero Energy Buildings (nZEBs) should also be operated according to the system. For grid-connected nZEBs, the combination of a reduced energy demand in the building and on-site production of heat and electricity to reach zero raises the issue of hourly mismatch between demand and production at the building level. This results in the need for exchange of electricity via the public grid even though the building has a net exchange of zero on an annual basis.

Measures at the individual building level that could solve the problem could be either flexible demand or the use of energy storage, i.e. electric batteries. However, as described above, within the context of the energy system, it is not the individual one building mismatch that is important, it is the sum of mismatches from all buildings that counts. Since all the buildings do not peak in consumption at the same time. When buildings are grouped into numerous buildings the mismatch of the individual building is levelled out at the aggregated level. The resulting mismatch of 1000 NZEBs is smaller than the sum of each mismatch of 1000 buildings.

This means that this mismatch should be solved at an aggregated building level since it is more cost-effective and beneficial to the system [24]. If one makes investments in flexible demand or storage at individual level, this adversely affects the overall system. Trying to compensate for each mismatch inside each building will lead to situations in which one building is charging a battery while simultaneously another building is discharging a battery. This only leads to unnecessary losses, and a severe over dimensioning of the storage space required in the system. Consequently, dealing with these problems from an aggregated system level saves money.

Furthermore, if flexibility is sourced from the buildings, separate from the needs of the energy system, then this risks competing for renewable energy from the system and this limits the ability for other cheaper technologies to utilise the renewable energy as would be done with system flexibility. Therefore, flexible demand should aim at contributing to the compensation of the aggregated mismatch of many buildings at the system level.

B.2 Operating the buildings from the building level

Despite the fact that buildings should have a limited role in providing flexibility and energy storage services, energy savings (heat, cooling and electricity) should be achieved at the building level through improved building operation and user behaviour - coupled with technical energy renovations in the existing buildings - since this is beneficial to the system in terms of energy and cost savings.

Table 4: The technical and behavioural savings and the increase in appliances

	Saving - technical	More appliances	Behavioural savings	Total savings	Savings (TWh)
IDA 2035	6%	-4%	8%	10%	0.89
IDA 2050	15%	-10%	20%	25%	2.22

In the IDA Energy Vision, the electricity savings were assumed to be achieved via technical efficiency improvements and behavioural changes (Table 4).

Research suggests that user practices have a decisive influence on the actual use of energy in buildings. The end-use of energy in identical buildings may vary by a factor of up to 3, due to different end-use practices of the residents [31,32]. It is thus essential that the buildings are operated appropriately by the users living in the buildings.

Rebound and pre-bound

Research shows that the smaller the heat demand, in accordance with the Building Code, the need for energy is relatively greater than intended by the theoretical calculated consumption [31]. This is generally due to changing standards and levels of comfort. It has been demonstrated that the end-use of energy in buildings with poor technical energy efficiency is on average considerably lower than anticipated in the standardised energy-calculations of the energy certification scheme for buildings in Denmark [31]. The actual end-use of energy in buildings with high technical energy standard is, in contrast, found to be higher than anticipated in these energy calculations. The energy certification scheme for buildings in Denmark suggests that the difference in annual energy consumption per square meter between a G-graded dwelling and a C-graded dwelling is approximately 140 kWh. This is in contrast to the estimation that the actual difference in consumption is no higher than 30 kWh (Figure 25).

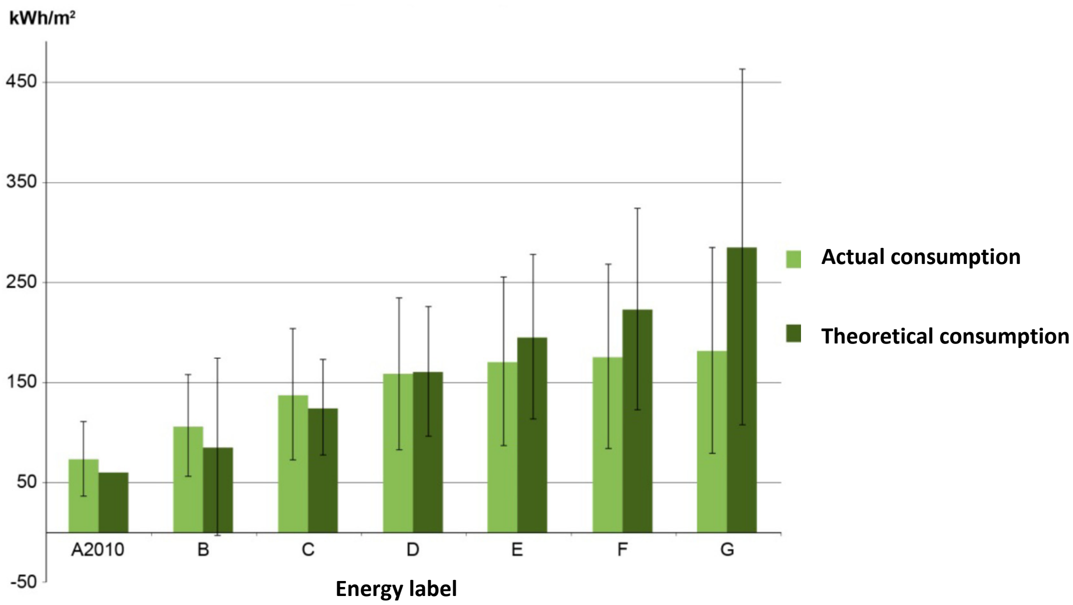


Figure 25: Comparison of average actual consumption and average estimated consumption for each type of energy label with the spread plotted on each column [31]

The findings are suggested to be the consequence of so-called "pre-bound effects" and "rebound effects". The idea of "pre-bound effects" is people living in a dwelling with a low technical energy standard and keep a relatively low indoor temperature, or they only keep part of their house heated. The idea of rebound effects is that residents in dwellings with a high technical energy standard develop less energy efficient practices. This is because part of the potential energy savings related to energy renovations are used to increase the comfort level of the indoor climate. It has been shown that on average 20% of potential savings from installing a heat pump is converted into increased comfort of indoor climate [31]. For summerhouses it has been shown that 100% of the potential energy savings are converted into increased indoor comfort [33].

Indoor comfort can go both directions; when the heat performance in increased in office spaces, there is a risk that cooling requirements and electrical demand increases instead [34]. It is thus important for the long term performance of the buildings to consider the re-bound and pre-bound effects when trying to improve energy performance.

Smart meters

In order to increase savings and address the rebound and pre-bound affect, ICT technologies that make buildings smarter have become more popular in recent years. This increase is even further strengthened because smart metres can potentially be used for energy savings or for flexibility services. As explained above, energy flexibility within the buildings will be limited in the future building stock, meaning that smart meters will be utilised less for this purpose.

Since smart meters can be connected to the electric and heating grid they could be utilised for saving energy as opposed to shifting it for flexibility. Smart meters can either be used for automatic or manual control of the building energy consumption. Automatic control could be done based on programmable settings and manual control could be achieved by the users controlling energy demand, or there could be a mix of the two. Both could be achieved through using energy and price information.

Smart meter data

Smart meter data is not only interesting for the user of the building. It could also help system operators optimise the electricity and thermal grids by:

- *Helping optimise the distribution grid or transmission grid by lowering peak demand (load shifting)*
- *Calibrating GIS models, used for planning*
- *Showing savings potentials*
- *Showing houses where users have bad behaviour*
- *For heat, helping locate at which substations heating temperatures could be lowered without any problems for the consumers, and locate problematic peak demands.*

It is important however that installing technology does not necessarily lead to the desired outcome, whether that be better consumer behaviour through energy savings or increased standards of living as explained above with the rebound and pre-bound effect [35].

B.3 Electricity and heating tariffs and levies for households

The general structuring of electricity and heating tariffs should be geared towards savings rather than flexible demand when considering the households and small consumers. Behavioural aspects are an important part of changing the level of electricity and heat demand, and when installing new technologies, such as better thermostats and smart meters or appliance level information these aspects should be taken into consideration. While economic incentives on their own do not always result in lower consumption, a restructuring of tariffs and levies can support information campaigns and efforts to change habits in the longer run.

The electricity consumption connected to appliances can be lower than today, and this can be promoted with electricity prices, combined with labelling of products and information campaigns. In such demands the potential flexibility demand (load shifting) is very limited compared to other parts of the energy system e.g. district heating or transport. This means that for households, tariffs and levies should promote a decrease in demands rather than flexibility. Where electricity is used for heating by for example individual heat pumps, there are higher potentials for moving demands and as mentioned elsewhere, passive heat storage could be used. Such flexibility can be used to integrate renewables but is rather limited due to storage sizes in individual houses and due to demands for heat being placed at specific times, where heat pumps may have to operate frequently due to high demands.

Electricity demands in the distribution grids is increasing due to more electric vehicles and heat pumps. Charging for peak capacity use may be considered to ensure efficient use of the distribution grids and to avoid a need for heavy expansion of these.

The tariff for district heating should reflect the long run marginal cost of providing district heat in renewable energy systems, including production and infrastructure for storage and distribution. There is a tendency to have a high fixed share for heat consumers due to the large long-term investments. Traditionally tariffs are based on a fixed share and a share connected to the short term marginal costs. To promote and give incentives for consumers to conduct heat savings consideration about making more or all of the tariff variable for the consumer could be made. This could be a separate tariff system for buildings where heat savings have been implemented. Also considerations on incentivising savings by charging for capacity could be made.

B.4 User knowledge, norms (meanings) and habits

It is important that when user behaviour is being changed in a building to save energy, not only technological solutions are integrated but other factors related to the people are considered as well. These other factors are related to what makes users practice certain behaviours in the buildings, and why it is so difficult to constitute real change in peoples' level of energy demand. People in the building act according to particular behavioural drivers, so it is important to understand what is dictating the particular behaviour of a person. One should not assume that all solutions, particularly technology, will lead to the desired outcomes since this is rarely the case; solutions are more likely to be a combination of all factors.

Outside of technical improvements, recent research has shown that user-behaviour is largely controlled via consumption practices that can lock users into particular patterns of energy consumption in which recently has become more intensive [36] (Figure 26). Three particular elements related to consumption practices have been identified in Gram-Hanssen (2015) and appear to provide a comprehensive definition of what controls user-behaviour in buildings. These elements include: 1) knowledge of the user, 2) user norms (meanings), and 3) user habits [37]. These three elements have been shown to be extremely important when dictating user-behaviour and they are largely formed through social norms and cultural and economic factors. These factors show that adopting sustainable ways of living do not depend on only diffusing 'green' beliefs and actions through society [38].

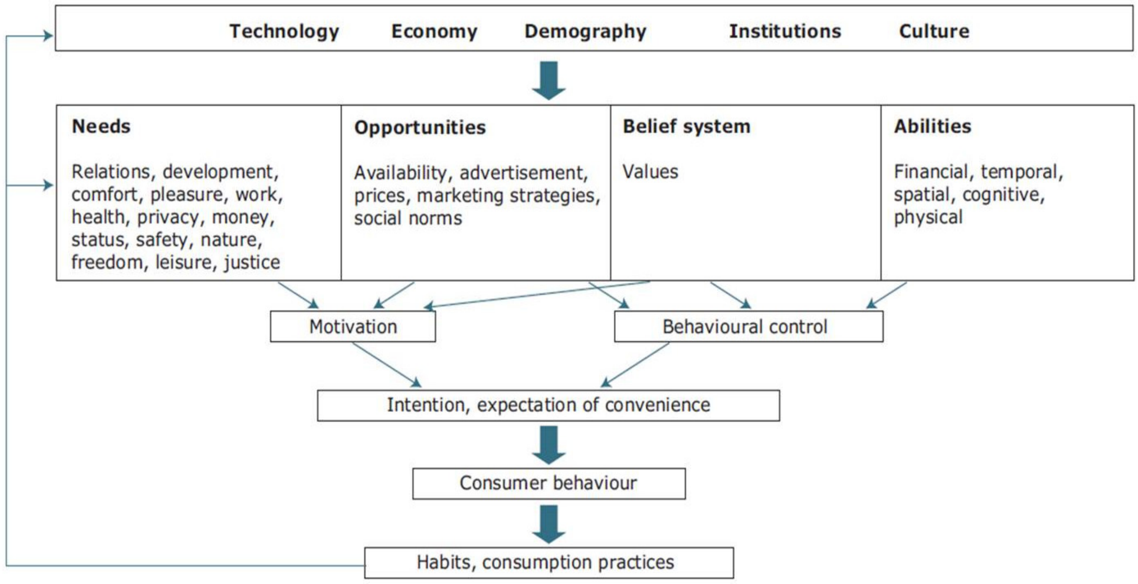


Figure 26: Main factors influencing consumer behaviour and emergence of consumption practices [36]

Improved knowledge is a relatively simple concept to understand and ameliorate since a user can always learn about new technologies and about how to use them and what they are for. Understanding and improving user norms (meanings) and habits, and achieving real change in them is more complex, time-consuming and difficult. All three elements, along with technology, are mutually dependent and equally important [37]. If these elements are not considered together when trying to achieve energy savings it can, and often does, lead to undesirable outcomes, such as the rebound or pre-bound effect [39].

User-knowledge is often seen as the most easily addressable element since it can be learned the user can obtain knowledge and integrate it into their daily user-practice. However, this improved knowledge can lack critical content or purpose, such as how much energy the technology should reduce, or even if energy should be reduced. An example is when users use a new heat pump. When a heat pump is introduced, the user can sometimes increase their preferred ambient room temperature, and thus their heat consumption [37,39]. Knowledge maybe missing about the purpose of having a heat pump, which is to use less energy rather than to increase comfort. Therefore, often the energy goes up which demonstrates that the knowledge of the user was not sufficient about what the heat pump was intended for. Thus, the user must learn that the technology, i.e. heat pumps, is for reducing energy consumption, and in addition to the technology itself they need new knowledge so their practices are in line with the desired outcome.

Norms (meanings), combined with habits, often dictate the daily practices of the user, which are defined by their normal behaviour in the building. Examples of particular behaviours would be users doing household activities like washing or watching TV at certain times of day, or on certain days in a week. Other norms could be related to privacy or social and economic status decisions, which can affect consumption levels [40,41]. For example, people may not believe that having smart meters collecting information about their private energy consumption is appropriate in their daily lives. Norms and meanings can be related to other social factors as well, for example if a user has previously not been able to afford heat but has desired it, then a heat pump will allow them to fulfil their expectations, which are a high level of comfort, but not necessarily to reduce heat demand, which could be above what was predicted. Thus, when designing intervention measures it is important to understand why certain norms (meanings) are created, what effects they can have on the user-behaviour and how these can be altered to ensure practices can be changed. To make sure that new energy savings measures also change user practice, some basic approaches include looking into how the buildings and new technologies change user-practice and vice-versa, [42].

Habits are also an important consideration which are related to the norms (meanings) of the user, and often knowledge reinforces habits as well. Consumption patterns in energy are generally created by habits and reflect that people are most often unaware of their routines and habits. Once the user has particular routines they create habits which may need to be changed or altered in the use of the building, but habits are notoriously difficult to change. An example of the persistence of habits is shown by looking at previous implementations of smart meters. These were installed to change the habits of the user by providing comparative feedback information [43], price information [44–46], or real-time information to the user. However, these types of implementations, based only on price incentives and improved knowledge, show limited success, likely due to engrained habits [47].

Gram-Hanssen (2015) explains that in Denmark, numerous studies have focussed on promoting energy-efficient technologies rather than on changing habits [37]. To address this, instead of keeping the focus on individual consumption, focus should be placed on the emergence and transformation of social norms as these lock people into consumption patterns.

Energy savings are most likely achieved only when these four elements are addressed successfully and simultaneously in energy savings measures, therefore this area must be considered and investigated with concerted efforts to addressing these behavioural elements if energy savings are going to be achieved. When designing policy this is relevant because the involved actors need to be involved from the outset of the policy process.

Cooling
In Scandinavian countries, and in Denmark, cooling demand exists and is growing [55]. Specifically for comfort cooling, what is necessary is often very culturally informed, and dependant on what the norms for acceptable and unacceptable comfort are [56] .

In the IDA Energy Vision district cooling is used as an efficiency improvement measure and an integration option between electricity, heating and cooling. Data from a new report about the cooling potentials in Denmark has been used as the reference point [57].

B.5 Recommendations for building operation and user behaviour

- Heating and electricity savings will likely not be achieved if only technical energy renovations are carried out in the building stock. It is necessary to **consider and address connecting technical energy renovations and operation (smart meters) to user behaviour in the building.** Electricity savings are mostly achieved through improved building operation and user-behaviour.

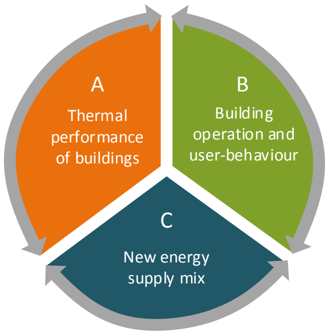
- Heating and electricity savings should be achieved with improved operation of the building (i.e. via smart meters, better appliances, thermostats etc.) and consumer behaviour. **Behaviour and user operation is key to the performance of buildings**, to the extent that end use of energy in identical buildings may vary by a factor of three. The pre-bound and rebound effects mean that even if buildings are renovated, the energy savings are not guaranteed. To address this appropriately when installing energy renovations and other technologies such as smart meters (that provide different information to the user or system operator), it is essential that three factors are considered: user knowledge, habits and norms (meanings). If these factors are addressed in isolation, not addressed, or not addressed together the chances of achieving heat and electricity savings are likely to be reduced.

- To optimise the potential of user-behaviour and operation of the building, it is important that the **operation of the buildings is according to the needs of the energy system**, and not optimised to the needs of the individual building. This is because the energy system in the future will be highly integrated, and for the energy system to operate properly it will depend heavily on the appropriate operation of the buildings. This means that buildings should not operate in isolation from the rest of the energy system or be optimised on its own.

- **Buildings should not be prioritised as a source of flexibility in the energy system** since the flexibility can be provided by cheaper means and more efficient technologies in other parts of the system, for example large-scale heat pumps, electrolysers, and large-scale thermal storage. Smart meters or flexibility in using e.g. heat pumps or regulation the heat demands have a potential to make contributions to reduce peaks for power plants and in production of district heating. The potential for integrating large quantities of renewable energy by using this flexibility is limited.

- There is **limited room for building level flexibility**, **building level energy storage and using integrated energy supply as a way to offset building level energy consumption (nZEBs).** Flexibility and energy storage services can be achieved more cost-effectively and with more success at the system level rather than the building level. Studies demonstrate that investment in passive heat storage is a cost-effective way of providing flexibility, but investments in heat accumulation tanks and batteries on the household level are not cost-effective. Energy savings in buildings are more important than building level flexibility.

C. New energy supply mix



	Today	Future (2050)
Level of district heating coverage	High	Very high
Low temperature district heating	None	High
Large scale heat pumps	Low	High
Individual heat pumps	Low	High
Individual boilers	High	Low

The heating supply for the building stock in 2015 comes from both centralised and individual sources (Figure 27). Centralised district heating supplies around half of the heat demand, mostly to densely built urban areas. Biomass or natural gas supplies most of the heat for buildings not connected to the district heating grid (Figure 28). A small share of buildings is supplied heat with heat pumps.

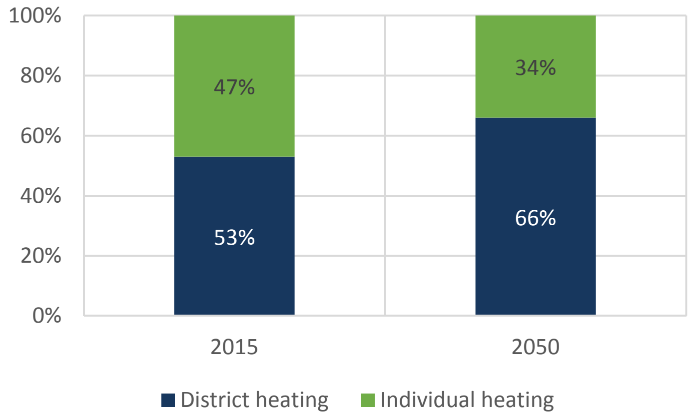


Figure 27: Proportion of total heat supply split between individual heating and district heating [1]

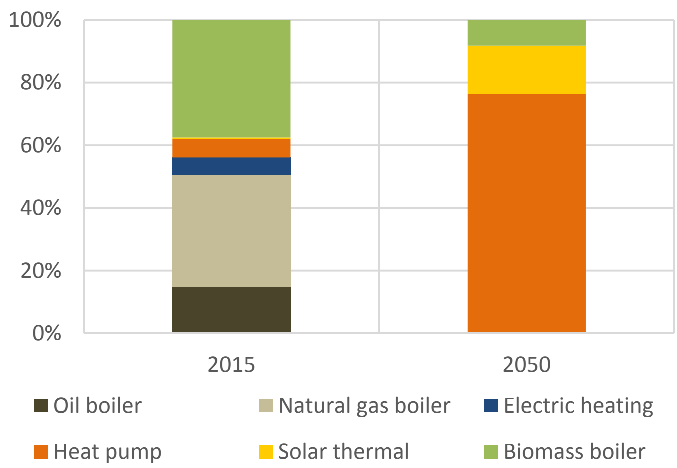


Figure 28: Breakdown of heat supply technologies within buildings outside of district heating areas [1]

In the future energy system, the buildings will need to have an even stronger relationship with the energy system by being part of the link between the thermal and electricity sectors; enabling more district heating and through a different mix of individual supply technologies, also shown in Figure 27 and Figure 28.

The most feasible solution is to combine a gradual expansion of district heating in urban areas with individual heat pumps in the less densely populated areas, while also implementing energy savings in the building stock. Low-temperature district heating can be expanded gradually as heat savings are implemented.

Micro-CHPs are often seen as a way to take advantage of the efficiency of cogeneration within the building. However, in future renewable energy systems such as the IDA Energy Vision, micro-CHPs are not competitive with regards to fuel, CO_2 emission and cost reduction compared to district heating and individual boilers based on biomass [48]. Analysis shows that ground-source heat pumps and in some cases air-to-air heat pumps in combination with solar thermal is more feasible than boiler options for individual heat solutions [48] (Figure 28).

The supply of electricity in the IDA Energy Vision is based on a high level of fluctuating renewables, including both on- and offshore wind power (15% and 60%, respectively) and PV (6%) [1]. Because these fluctuating sources make up more than 80% of the electricity supply, a high level of flexibility is required in the system.

C.1 District heating

In the future renewable energy system, the proportion of buildings supplied with district heating will increase as shown above. The Heat Plan Denmark analyses used GIS (Geographical Information System) tools to identify the cost of expanding district heating and heat savings [25,49]. The studies showed that in an overall energy system perspective, a substantial reduction in fuel demands and CO_2 emissions as well as costs could be achieved by connecting more buildings to district heating. Looking towards 2050, the analysis indicated that a feasible solution will be to expand district heating to somewhere between 63% and 70% (Figure 27). Sixty-three percent could be achieved by adding buildings in neighbouring areas, which today are mostly supplied by natural gas, and 70% could be achieved by additionally adding buildings within a distance of up to one kilometre from existing district heating areas. The Heat Plan Denmark studies also concluded that heat savings are essential for improving the system [25,49]. Using GIS, the cost of saving levels were assessed in comparison to the production cost of district heating.

Heat Roadmap Europe

Based on the methodology of Heat Plan Denmark, the future heating of buildings in Europe has been investigated (www.heatroadmap.eu). Research shows, based on GIS and energy system analyses, that heat savings are feasible up to between 30-50% of current level. The current waste heat from electricity production and industrial sources could nearly cover all heating demands in Europe if exploited in district heating. At least 50% district heating seems feasible in Europe as the majority of citizens live in densely populated areas with nearby heat sources available [58].

Integrating renewables through district heating

In addition to being cost-effective, district heating plays an important role in integrating renewable energy into the thermal sector and providing flexibility in the system, by linking the thermal and electricity sectors. The use of district heating through heat pumps and CHPs is one of the key aspects of system flexibility. Additionally, district heating helps utilise heat production from low impact and renewable sources such as waste incineration and industrial excess heat production.

Low temperature district heating also helps the further integration of the following energy sources:

- Geothermal heating
- Large scale heat pumps
- Biogas production
- Solid biomass such as straw

Upgrading today's third generation district heating (Figure 29) to fourth generation district heating (low-temperature district heating) can lower costs and lower biomass demands. Therefore, it is highly beneficial to have low-temperature district heating connected to the building stock. Examples of low-temperature district heating solutions already exist. New concepts and system components are still being developed or at a research stage.

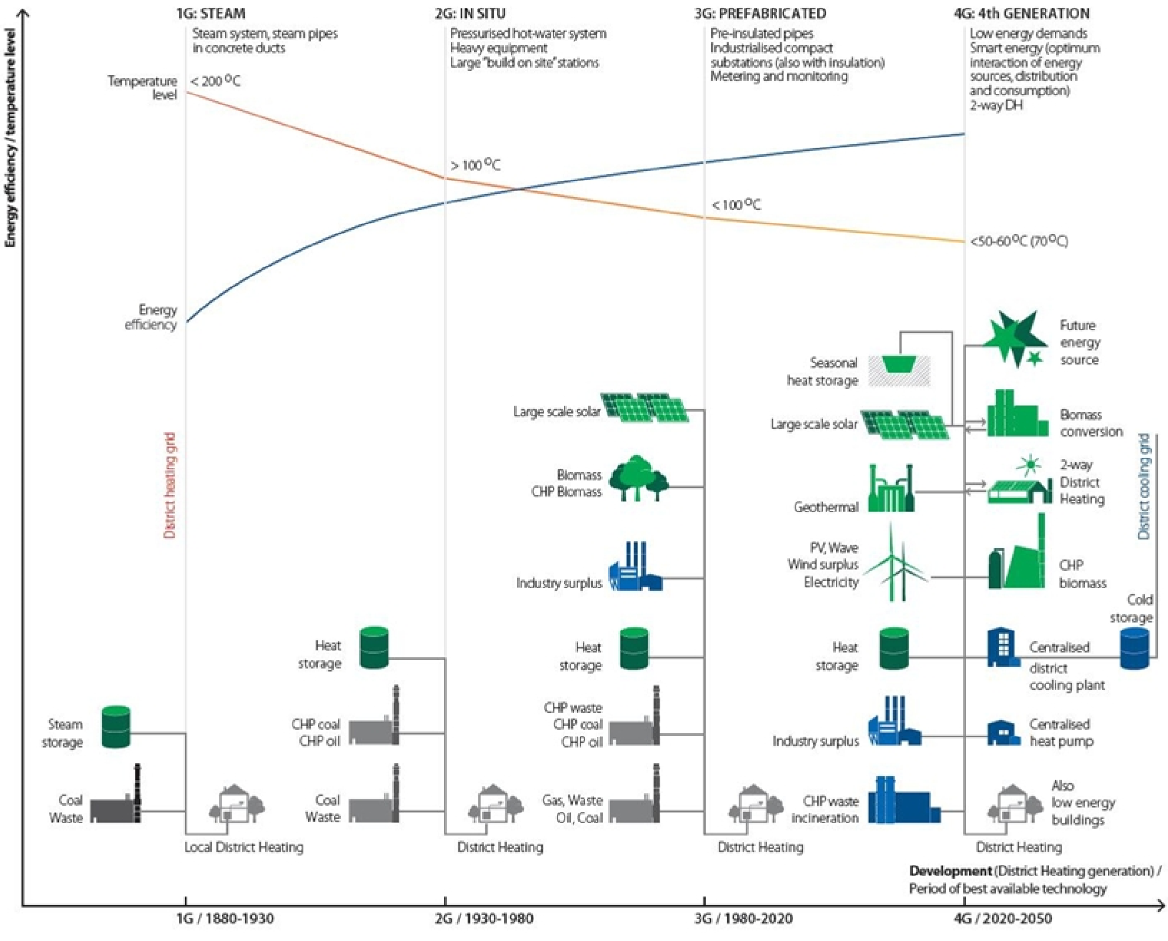


Figure 29: District heating evolution from the first generation in 1880-1930 to the fourth generation expected in 2020-2050

Low temperature district heating

Low temperature district heating is when the temperature at which the heating is supplied to the building is reduced from currently 75-90°C. Low temperature district heating infrastructures exhibit low heat losses, are able to store more energy in the form of hot water, utilize renewable energy sources, and are able to collect heat from large heat pumps more efficiently, from solar thermal, geothermal and excess heat from industrial processes [50]. By means of smart thermal grids low-temperature district heating assists the synergetic development of sustainable energy systems [51].

The potential for the introduction of low temperature district heating is increased when heat savings are realised in the building stock. By reducing the heat demand of the buildings through improved energy efficiency, the capacity of the district heating grid and production units also allows for more buildings to be connected to the same grid. In this regard savings in the building and low-temperature district heating create synergies [51]. For example, floor heating or wall heating with an average water temperature just a few degrees higher than room temperature is also a possibility if the building envelope is sufficiently insulated and some passive thermal storage exists [52]. This can enable cost-efficient flexibility of heat demands.

In general, it is not always necessary to modify the space heating system in the building to ensure thermal comfort if the district heating temperatures are lowered. In some cases, though it can be expected that a few radiators need to be replaced. This mainly depends on the return temperature that is desired, which in turn depends on the pipe sizes in the district heating network and heat exchangers. For the single-family houses it seems possible to supply heat with temperatures around 55/35°C and 45/35°C without making any large changes in the space heating systems. Comfort problems with the current radiators are not expected. However, the necessary changes also depend on the building type, and this has not yet been investigated e.g. multi-storey buildings. Instead of replacing the radiators, energy renovations as described in Part A should be made to allow the heat demand to be lowered [53]. The change in efficiency may be further improved by introducing heat exchanging technologies that can use supply temperatures of 40 °C and return at near room temperature (20-22°C) [51,53].

It is expected that the hot water supply in the buildings will need to be modified if the supply temperature is lowered to a certain degree. With a lower supply temperature of 45°C, for example, the domestic hot water supply may need to be modified to avoid problems with Legionella (a bacterium that is not problematic under high temperature conditions) [54]. The modification needed depends on the building type (e.g. single-family, multi-storey). These kinds of challenges are being investigated, and the research performed so far is mainly theoretical and based on case studies and it is recommended that more research and development is done in this area.

4DH strategic research centre

4DH (www.4dh.dk) is an ongoing research centre with the purpose of developing what 4th generation (low temperature) district heating can look like, and how it can contribute to the energy systems of the future.

C.2 Heat pumps

Although district heating can be expanded in the future, the remaining buildings (in mostly rural areas) should be heated using electric heat pumps supplemented with solar thermal energy, which seems to be the best alternative to district heating [25] (Figure 28). The benefits from installing heat pumps are evident on the building and the system level [29]. Research shows the economic gains of installing heat pumps from an end-user perspective are mainly related to energy savings, due to their efficiency compared to boilers. Heat pumps, especially ground-source, are very energy efficient with an average COP of around 3 or more, meaning that one unit of electricity input leads to three units of heat energy output. This is far more efficient compared with boilers. This means that heat pumps can utilise renewable electricity and save on primary energy consumption significantly. On the other hand, investment costs are higher than for boilers.

The main types of heat pumps include ground-source heat pumps and air-to-water heat pumps, but based on previous research [25], ground-source heat pumps should be prioritised since the COP is higher in colder periods during the year, leading to better efficiencies [60]. Ground-source heat pumps and air/water heat pumps are typically supplemented by an electric boiler to cover peak loads, in order to limit heat pump investment costs [25].

For the system, the heat pumps are an important consumer of renewable electricity. By utilising the heat pumps during periods of high renewable electricity production this allows less curtailment of the production. Heat pumps can deliver heat to a building at times when it is not needed, and it can be passively retained in the living space for when the occupant is present. The combination of passive storage with heat pumps is one area where buildings can contribute to the flexibility of the system cost-effectively. In order to achieve this, the buildings need to be energy efficient so that the heat is not lost. Thus, this stresses further the importance of energy renovations.

The expectation is that biomass will provide a small share of the rural heat supply as well, but this is less preferable. Firstly, biomass boilers do not provide the same link between the thermal and electricity sectors, so there are no external synergies that can be capitalised on by the energy system. Secondly, biomass will be seen as a scarce resource in a 100% renewable energy system and highly valuable for transport and electrofuels, and the opportunity cost of using it for space heating and hot water is high. This means that while some level of biomass boilers is inevitable, where individual heating is appropriate, the focus should be on efficient and synergistic, preferably ground-source, heat pumps.

C.3 On-site energy supply

Buildings may also contribute to their own heat and electricity demand through integrated on-site electricity production. One example is by supplying electricity for the building via PV.

In the IDA Energy Vision, it is cost-effective for PV to provide 6% of the electricity. This requires an increase in capacity to 5000 MW by 2050 [1]. Some of this capacity will be installed on the rooftops of buildings, based on technical compatibility and cost-effectiveness towards the system. However, although it is appropriate for buildings to have individual PV it is also important that these technologies remain connected to the grid.

By keeping on-site electricity production like PV connected to the electricity grid, overinvestments in capacity can be avoided. This relates closely to the most effective sources of flexibility throughout the system. Having a disconnected on-site energy supply involves having a certain amount of storage or flexibility on the building level, as well as sufficient capacity to cover peak demand.

By having the building as part of the system, the mismatch between production and consumption of electricity on the building should not be seen as a problem to be fixed through flexible demand or energy storage, but from the system point of view it should be seen as a positive asset [24]. The mismatches between the buildings' supplies and demands become aggregated through the system, and are levelled out. This reduces the need for capacity, and is a cheaper source of flexibility than disconnected on-site energy supply.

This means that when viewing the buildings within the system, as opposed to independent units, it is ultimately not critical to have PV and solar thermal sitting on top of any specific individual building. Primarily, these technologies should be located where it is most feasible to have them [23].

Furthermore, by understanding the mismatch of different on-site energy production and demands on the individual building level within the context of the energy system, this means that the individual units may need to be increased or decreased in size depending on what the system needs to be most cost-effective [24].

If electricity is produced onsite, the electricity that is not consumed by the building and that is sent to the grid should not be counted as offsetting electricity consumed from the grid by the building, as it is for nZEB calculations of net primary energy. It is often not beneficial to the energy system for individual buildings to use isolated calculations of primary energy demand in order to achieve nZEB status. In theory, this allows for worse building performance in the sense of building envelopes, windows, roofs etc. as long as there is a high level of on-site energy production.

Integrated renewable technologies should not be seen as an alternative to energy savings in the buildings as is often done in nZEB calculations. These technologies should be seen as a supplement to energy savings, and the energy production technologies as helping the system. The building should meet a specific heat and electricity demand per square metre that is most beneficial to the system as described in Part A. Then, the operation of the building should be calculated based on the needs of the entire system, as was described in Part B, as opposed to achieving a nZEB status via deductions of onsite energy production.

C.4 Key facts and recommendations

- The flexibility required to integrate fluctuating renewables is realised by integrating the thermal, power and transport sectors towards 2050. The improved efficiency in the building stock will help create synergies between these sectors in the wider energy system, by allowing more integration between the thermal and power sectors. With increasing fluctuations in the electricity supply caused by wind power and PV, this calls for solutions to increase the flexibility of the system. **Buildings can contribute to a Smart Energy System by enabling a new interplay with energy supply technologies that maximise the synergies in the system, such as (low-temperature) district heating and in some buildings district cooling in dense areas, and individual heat pumps in less dense (rural) areas.** By utilising these two technologies this means that more benefits can be achieved at the system level by integrating more renewable energy technologies and cheaper energy storage technologies.

- **Individual micro-CHP options or biomass boilers do not seem to be desirable,** neither in terms of fuel efficiency nor from an economic point of view. Biomass boilers however will be used to some extent in the future although biomass can be allocated better to other purposes than heating and used more efficiently.

- It is cost-effective for the energy system to **increase the share of district heating from around half of the heat supply today to around two thirds in 2050**. This is based on analysis that used GIS mapping to determine the costs of installing new pipelines and district heating infrastructures as well as energy system analyses. Moreover, the expansion of district heating will help utilise heat production from waste incineration and industrial excess heat production, geothermal heating, biogas production (supply of heat), and solid biomass such as straw.

- Coupled with increased district heating and heat savings in buildings, the temperature of the **heat supplied to the buildings can be gradually decreased towards 2050** to save primary energy demand but also to enable integration of new renewable energies, excess heat from industry, large-scale heat pumps and energy storages at the system level. It is uncertain how the buildings will need to be upgraded to receive lower temperature district heat since this research is ongoing, but it is likely that most radiators installed today will be sufficient in the future. Smart meters could facilitate good solutions and help monitor changes in the operation of the building.

- **Individual heat pumps seem to be the most cost-effective alternative to district heating for buildings too far from district heating grid**. This is because heat pumps provide external benefits to the energy system through high energy efficiency, by electricity consumption, and by having some level of flexibility. They are the individual heating alternative that fits best into a cost-effective 100% renewable energy supply, also because they place the least pressure on the amounts of biomass and wind required in the system. Ground-source heat pumps should be promoted as the COP is higher than air-air heat pumps during the colder winters. On-site solar thermal heat production units should be installed on buildings to assist heat production units such as heat pumps or biomass boilers.

- It is important that **energy efficiency and building integrated energy production are regulated independent from each other** in order to avoid that for example the installation of PV, solar thermal or individual heat pumps will lead to less renovation levels and decreased energy performance in the building.

- The future energy system will have a higher share of PV, with at least 5000 MW capacity installed, however it is **important that PVs (and other electricity producing units) are installed where it is most cost-effective and appropriate for the energy system**. It is not necessary to install solar PV on all buildings, and it can be inefficient to install solar PV on buildings in order to offset in-building energy consumption (for example in nZEBs). All electric energy production units should remain connected to the grid and interact with the system. In addition, on-site electricity storage should be avoided since this is not beneficial to the system and leads to higher energy system costs.

3. Discussion and conclusions

The aim of this report is to provide a research-based reference guide on buildings, clarifying the role of buildings in a 100% renewable energy system. More than 50 reports and research papers have been reviewed and more than two decades' knowledge about the interactions between different components of the energy sector has been included. The IDA Energy Vision 2050 provides a context for the understanding of how a 100% renewable energy future is technically possible and economically feasible. There are other reports with scenarios for 2050, however this vision provides details on the built environment that can enable an understanding of how the building stock would have to change to fulfil its future role in an integrated, cost-effective, complex renewable energy system.

The IDA Energy Vision, in congruence with other 100% renewable energy system scenarios, places a clear importance on the role of the building stock. The most important recommendation for buildings in the future energy system is that energy renovations are necessary in existing buildings. Existing buildings, especially pre-1980, have a much larger impact on consumption per square metre and will continue to be the largest part of the building stock in 2050. Forty percent heat savings can be recommended in the existing building stock as a whole. Even if new techniques and materials are developed to improve renovation, the challenge remains to be able to implement the policy measures necessary to reach these very ambitious levels of renovation. All general building renovations need to consider energy aspects, as the frequency of renovation of the individual building is very low. For new buildings it is key to separate standards for the building envelope and production of renewables in regulation. Strong demands should be put on insulation levels and there should be strong incentives for renewable energy production such as PV where feasible and cost-effective. The supply in new buildings should be low temperature district heating in cases where that is feasible; otherwise ground-source heat pumps can be recommended, occasionally in combination with solar thermal.

The challenge to actively work with people and change their habits, norms, and long-term behaviour is something that will have to be addressed in the future. This cannot only be achieved through technical developments in insulation and thermostats alone, but requires a policy approach that takes into consideration the use of buildings in order to really constitute change and sustain low consumption over time.

Investments in balancing of supply and demand are not cost-effective at the building level in renewable energy systems. The IDA Energy Vision 2050, the Smart Energy System concept is based on the integration of the sectors, which allows for flexibility with substantial amounts of wind power and PV. The influence of building level flexibility is limited and local storage is not as cost-effective or resource efficient as flexibility based on the integration of the sectors in the energy system. This means that an expansion of district heating is recommended to cover two thirds of the Danish net heat demands. If savings are achieved, lower temperature levels can be delivered in district heating networks, which increases the efficiency of large solar thermal and heat pumps as well as allowing for increased use of waste industrial heat, incineration, geothermal etc. Savings would also increase the efficiency for heating outside district heating areas via ground-source heat pumps which are recommended.

In this report, levels of savings have been described for existing and new buildings and other elements have been quantified based on the review conducted. Such quantifications are sometimes hard to compare across reports and analyses. The aim in has not been to come with exact levels. The messages and conclusions in this report point in directions and gives guidelines as to which levels and which elements are more important than others.

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