

Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time

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Abstract Residential and service (office) buildings consume a large proportion of primary energy in Europe in the form of electricity and all other energy carriers. In response to this, the concept of near Zero Energy Buildings (nZEB) has been developed. These buildings have very low energy demands and integrate renewable energy to supply residual demand. nZEBs aim to increase energy efficiency from a demand-side user perspective. When looking at the entire energy system, there are also energy efficiency gains to be achieved on the supply-side. For example, from a district heating system. If an energy system becomes more efficient on the supply-side, then the question is how much energy needs to be saved on the demand-side, for instance by low energy buildings such as nZEBs. The purpose of this paper is to analyse and understand the implications from building new low energy buildings, i.e. nZEBs, within an energy system that is (a) transitioning to 100% renewable energy and (b) has substantially improved supply-side energy efficiency. A case study from Denmark is used to understand the outcome for the energy system when these new buildings are built in this context. The methodology and results of this study could be replicated for other European countries as well. The analysis looks at the total energy system heat savings, costs and biomass consumption. The paper shows that these new low energy buildings with very low heat demand do not

deliver the expected benefits for the 100% renewable energy system transition in Denmark. This is due to the increased efficiency and flexibility of the energy supply system in the future. However, deep renovations of existing buildings are necessary. Furthermore, this paper demonstrates based on the Danish case, that as European countries decarbonise their energy systems over the next decades, they will need to carry out detailed energy system analysis to determine the extent to which heat demand should be reduced in buildings within the context of the transitioning energy system.

Keywords Renewable energy · Energy efficiency · Energy system · Greenhouse gas emissions · Zero energy buildings · Buildings

Introduction

The European Union wants to reduce greenhouse gas emissions (GHG) by 80–95% compared with 1990 levels by 2050 (European Commission 2011). To achieve this, significant reductions will be required in the energy sector, specifically for electricity generation, thermal energy and mobility. Emission reductions should be achieved by reducing energy demand by changing consumer behaviours (Gram-Hanssen 2013), increasing efficiency via technology improvement and implementation (Lund et al. 2014a) and implementing renewable energy into the energy system by replacing current energy technologies (Lund 2006). Overall, there needs to be an overhaul of the energy system, and all of its

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components will play a role in ensuring that this overhaul is successful.

One of the main components in the energy system is the building stock. Today's buildings demand around 40% of the energy consumed in Europe for electricity, heating (including cooking) and cooling (BPIE 2011). This includes residential and commercial buildings, of which most are built within cities. Consequently, most GHG emissions that arise from cities are from buildings. Numerous city initiatives focus on the building sector to improve energy efficiency (especially for heating), increase the penetration of renewable energy and to reduce GHG emissions.

One approach to make the energy system more efficient and to reduce GHG emissions is by building near Zero Energy Buildings (nZEBs). According to the EU Directive on energy performance of buildings (EPBD), the definition of a nZEB is a "*building with very high energy performance where the nearly zero or low amount of energy required should be extensively covered by renewable sources produced on-site or nearby*" (European Parliament and the Council 2010). In 2010, the EPBD made a mandatory requirement for nZEBs where the deadline for building nZEBs for public buildings in Europe is 2019 and for all other residential and non-residential buildings from 1 January 2021.

In Article 9 of the EPBD (BPIE 2015), all member states are required to make a national nZEB definition, defining energy performance levels (herein referred to as net primary energy demand which is measured per square metre). Subsequently, in the building codes of most countries, the net primary energy demand of future new nZEBs has been defined.

A nZEB building is defined by the boundary around the building and measuring the energy import and export across this boundary, which is usually calculated based on delivered energy minus exported energy (Kurnitski 2013). A simple diagram shows this concept in Fig. 1. If the building produces energy within this boundary and consumes it, then it is not included in the calculation. Energy that crosses the boundary is multiplied by the primary energy factor for the energy carrier, i.e. electricity. The primary energy factor is defined by the country and is calculated based on the fuel mix used to produce the energy. Energy exported from the building over the boundary is multiplied by the same primary energy factors, and the result is deducted from the net primary energy demand of the building.

In summary, nZEBs differ from passive buildings by combining energy efficient building design with on-site or nearby renewable energy technologies, for example solar photovoltaics (PV), in order to reduce the net primary energy demand of the building to close to zero. Thus, nZEBs aim to achieve the efficient use of energy, as well as renewable energy generation and consumption (Torcellini and Crawley 2006).

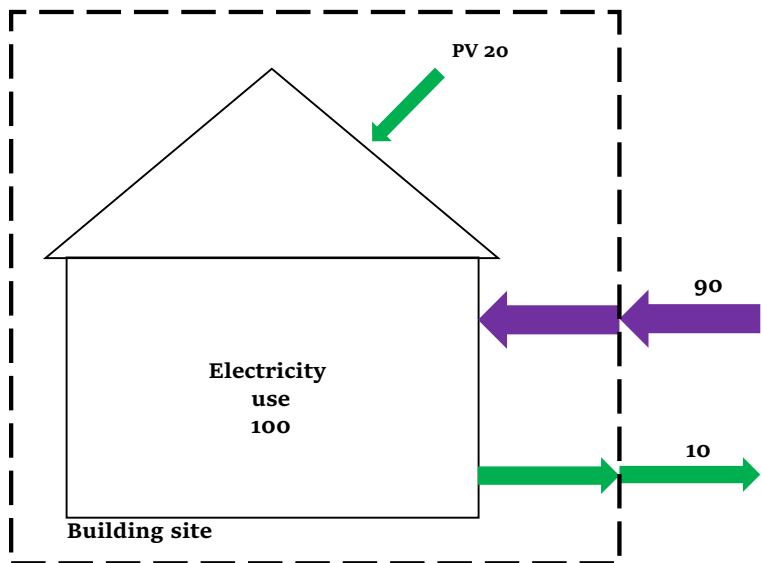
Although numerous studies have investigated nZEBs and the design of them, to the knowledge of the authors, there has not been any investigation into understanding the system level impact of the improved energy performance level of these buildings based upon system level analysis as opposed to individual building level analysis. In other words, an analysis in which the system level perspective is used to identify the positive or negative impacts from building these low energy buildings.

Numerous studies describe in detail the nZEB concept: its calculation methods and its beneficial principles (Sartori et al. 2012; Marszal et al. 2011; Kurnitski 2013). Review studies have been done to determine the potential future contribution of nZEBs and their applicability. Kylili et al. (2015) investigated the potential contribution of nZEBs to achieve smart cities in Europe based on the provisions of a nZEB and how they can be an integral part of a smart city. These results were based on a review of numerous studies on nZEBs.

Research efforts that have focused more specifically on real-world or simulated nZEBs investigate their main contentious aspects, such as usefulness for improving energy efficiency, their cost optimality and their load matching and grid (electricity) interaction. Often the research is based on the building level perspective. Pikas et al. (2014) investigated office buildings in Estonia, looking at the optimal external wall insulation thickness, cost optimal energy efficient solutions, and optimal PV panel size. In Finland, Mohamed et al. (2014) investigated numerous nZEB balances for a single family house, a standard house and a passive house using conventional thermal energy systems and micro- and small-scale biomass-based CHPs. The assessment criteria were primary energy, CO₂ emissions and cost. Fokaides et al. (2014) investigated the potential contribution of nZEBs to the energy demand of the Cyprus building stock based on the evolution of the building stock following the legislation in Cyprus.

Regarding load matching and interaction with the electricity grid, Voss et al. (2010) investigated load matching and grid interaction of nZEBs where analysis

Fig. 1 This figure shows the electricity use of the building (100) and the on-site or nearby electricity produced by PV within the system boundaries (20). The figure shows the exported electricity (10) and the remaining amount of electricity imported from outside the system boundaries (90). The imported and exported electricity is multiplied by the primary energy factor for electricity. The figure is sourced from Kumitski (2013)



of example buildings from Portugal, USA and Germany were done to propose indices to describe both these issues for nZEBs. Lopes et al. (2016) looked at load matching and grid interaction at a wider community level. Modelling analysis was done for three distinct scenarios (no demand side management, with demand side management and community level) where five Net ZEBs worked individually or in community.

On an energy system level, Lund et al. (2011) investigated the potential to integrate excess electricity from nZEBs from local renewable generation on the wider energy system based on a Danish case study. The study found that there is a need to assess the large-scale development of nZEBs, and based on their integration with the electricity grid determine, the optimal size of electricity producing units at the buildings based on a mismatch factor.

Despite these research efforts, to the knowledge of the authors, a study has not been undertaken to examine the impacts of these low energy buildings based on a whole energy system level perspective and analysis, especially within a transitioning energy system. Thus, the aim of this paper is to investigate the beneficial contribution of the large-scale implementation of low energy nZEBs (residential and office buildings) in an energy system that is transitioning to 100% renewable energy by 2050. To do this, a case study from Denmark will be used. The paper will demonstrate the role of buildings, especially new buildings, within the transitioning Danish energy system and the extent that

new buildings should lower their heat energy demand. Buildings in this paper include residential and service (office) buildings which make up 85% of the floor space and the majority of the heat demand of the building stock in Denmark. The other 15% are buildings, such as hospitals, schools and hotels that are excluded due to a lack of data. New buildings are referred to as “nZEBs” since this is what is required in the Danish building code. A key element of a nZEB is to have low end-use energy demand; therefore, this paper focuses on this aspect, but particularly on the heat demand since this accounts for the majority of the energy demand of the building, and the analyses is on the impact of low heat demand based on the Danish energy system perspective.

Danish case study

Denmark was chosen as a case study because it presents ideal conditions for this type of analysis. The energy system is already advancing towards 100% renewable energy with an already high proportion of wind power in the electricity mix (close to 50%) and a high proportion of district heating in the heat supply (over 50%). Furthermore, numerous detailed studies have been done in the country on how the energy system could transition to 100% renewable energy by 2050, and this provides a robust basis for this study. Furthermore, Denmark has set ambitious standards for nZEBs in its building codes, and these standards will be assessed within the energy system context.

Despite the Danish conditions, they are not unique to Denmark, and this type of analysis could be replicated in numerous other European countries by analysing their own energy system: its transition to 2050 and the building stocks and building standards. The relevance of using Denmark as a case study is to provide a methodology that can be replicated and to provide results and discussion points to encourage further research in other countries. The methodology can help other countries determine the role that their building stock will have in their future energy system.

The study will assess the current Danish requirements for net primary energy demand for new residential and office buildings and the future suggested Danish building code requirements. These are described in the next section.

nZEBs in the Danish building code

In 2008, the Danish government made a political decision that the net primary energy demand for new buildings should be reduced by 25% every 5 years from 2006 to 2025 (Thomsen 2014; Dyck-Madsen & Jarby 2016). This means that all new buildings built from 2025 onwards are expected to have a net primary energy demand of 0 kWh/m² y.

The net primary energy demand in Denmark is called an “energy frame”, which will be used herein. The current energy frame defined in the Building Code 2015 (BR15) for new buildings are presented in Table 1 below (Thomsen 2014). The calculation of the energy frame of the building considers the end-use energy demand which includes heating, ventilation, domestic hot water, cooling and electricity for operating the building, electricity for lighting (non-residential) and a potential overheating (+26 °C) penalty. Renewable

energy supply is deducted from this, as well as exported energy from the building. Renewable energy is for example from locally produced heat (solar thermal) and/or electricity from solar PV or wind for example. Bio-fuels are treated as fossil fuels and have a primary energy factor of 1.

Currently, the standards set for buildings built from 2015 to 2020 in BR15 are mandatory, and the energy frames for after 2020 are voluntary (Thomsen 2014). There is ongoing debate about whether the voluntary frames for new residential and non-residential buildings after 2020 should become mandatory after 2020. The purpose of this paper is to discuss whether these voluntary energy frames should be made mandatory in the Danish building code based on the results of the energy system analysis. This is done by analysing the impacts these low energy buildings make as the Danish energy system transitions to 100% renewable energy by 2050.

Existing buildings in the Danish building code

For existing buildings, there is no mandatory energy performance requirement (energy frame) for the building after renovation/retrofit. This is because of the large diversity of existing building types, which makes it difficult to set a standard requirement. However, for the building elements used in the renovation/retrofit of existing buildings, there are mandatory energy performance requirements. Building elements include construction elements and windows in the building envelope and the installed elements such as ventilation systems, boilers and heat pumps. Requirements are set for *U* values for walls and doors for example, and linear losses for joints between external walls and windows for example. The expectation is that the energy performance of the building is improved based on the sum of the

Table 1 Energy frame (The energy frame in Denmark includes thermal bridges, solar gains, ventilation, heat recovery, cooling, lighting (non-residential buildings), boiler and heat pump efficiency, electricity for operating the building, and sanctions for overheating. The mix of energy end-uses differs between countries

but it always excludes the energy use of residential building lighting and appliances. However, in non-residential buildings the lighting is included.) (net primary energy demand) of new Danish nZEBs in the BR15 and voluntary energy frames defined after 2020 and 2025 (Thomsen 2014)

Time period	New residential buildings (kWh/m ² y)	New non-residential buildings (kWh/m ² y)
2016–2020	= (30 + 1000)/(heated gross floor area)	= (41 + 1000)/(heated gross floor area)
2021–2025	20	25
2026–onwards	0	0

energy performance of these building elements in the renovation/retrofit (Aggerholm 2013). Therefore, the extent of renovation/retrofit determines the reduction of the heat demand of existing buildings.

Structure of this paper

This paper is structured in two parts. The first part describes the energy system configuration in Denmark and how it is expected to change as it transitions to the 100% renewable energy system. Some of the important components of the system will be described. This part helps to illustrate the context in which the new buildings will be built.

The second part describes the Danish building stock and how it is predicted to change from 2015 to 2050. The building stock includes the existing and new buildings. This part provides some insight into how many new buildings are predicted to be built in the future and what their energy demands will be. It also illustrates some details about the existing buildings.

In order to understand the impact of new buildings on the future 100% renewable energy system, an analysis for new buildings with different heat demands using six scenarios is done in the second part. The impacts are analysed in terms of (1) the total heat demand of the building stock, (2) the impact on biomass demand and (3) the total energy system costs. As the energy system transitions to renewable energy, these are the key sustainability criteria that low energy buildings such as nZEBs are expected to be beneficial.

The paper will conclude with a discussion about new buildings (and nZEBs) and their role in the future energy system in Denmark and in other European countries. Based on the energy system of today and the future in Denmark and Europe, conclusions will be made about the required energy performance of new buildings and the methods in which these are determined.

Danish energy system transition to 100% renewable energy

In 2012, a political decision was made in Denmark to achieve 100% renewable energy supply by 2050. In response to this goal, numerous research studies have been carried out to investigate how this could be achieved (Dyrelund et al. 2008; Mathiesen et al. 2009; Lund et al. 2011; Mathiesen et al. 2015a; Energinet.dk

2015; Danish Energy Agency 2014). In Lund et al. (2011), a new energy system concept presented how Denmark could achieve 100% renewable energy. This system is called a smart energy system, and this systemic approach will be used as the framework from which the new buildings in Denmark will be assessed within this paper.

Smart energy systems

The smart energy system (i.e. 100% renewable energy system) is a radical redesign of the system that exists today. A redesign is deemed necessary in order to cost effectively transition to 100% renewable energy and to integrate a large amount of fluctuating renewable electricity. In addition, at the same time maintain sustainable biomass consumption. Compared to the energy system of today, it is “smart” because it seeks out all opportunities to make the future renewable energy system as efficient and cost-effective socioeconomically as possible, and in doing so, it leads to a robust but more complex energy system. It is designed to create more interactions between the different energy sectors, and these interactions are shown in a simplified way in Fig. 2. The system has been developed using a computer simulation model (EnergyPLAN) and heuristic analysis.

The smart energy system is designed based upon a national level system analysis including all energy sectors at once, including electricity, heating and cooling, gas and mobility. All the energy consuming components including buildings, industry, mobility and agriculture are included. The entire system is balanced on an hour-by-hour basis over 1 year (2050), where all energy demand and supply is matched near perfectly in each hour in each energy sector. This means that decarbonisation is achieved with the least cost, and the system design has numerous synergies between the energy sectors. For example, electricity and transport are synchronised via electric vehicles.

The smart energy system combines the electricity, thermal and transport sectors so that the flexibility across these different areas can compensate for the lack of flexibility from renewable resources such as wind and solar (Mathiesen et al. 2015b). In order to combine the energy sectors, the system comprises of three smart energy grids. These smart grids allow for better energy efficiency in the system by improving inter-sector integration, the addition of energy

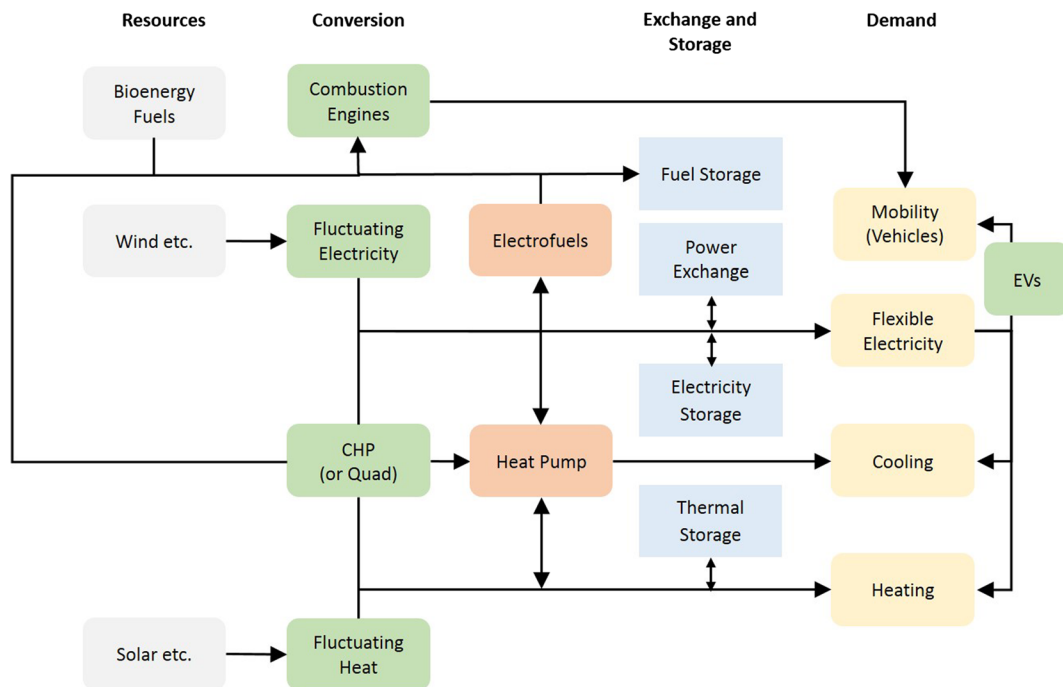


Fig. 2 Simplified illustration of the energy flows (arrows) in the 100% renewable energy scenario between resources, conversion technologies, exchange and storage and demand. The figure is sourced from Mathiesen et al. (2015b)

storages and the creation of synergies between energy sectors (Mathiesen et al. 2015b).

- Smart electricity grids are required to connect flexible electricity demands, such as heat pumps and electric vehicles to the intermittent renewable electricity resources such as wind and solar power.
- Smart thermal grids (district heating and cooling) are required to connect the electricity and heating/cooling sectors. Thermal storage can be utilised to create additional flexibility, and heat losses in the energy system can be recycled.
- Smart gas grids are required to connect the electricity, heating and cooling, and transport sectors. Gas storage can be utilised to create additional flexibility. Liquid fuel storage can also be utilised if the gas is transformed into a liquid fuel.

In order for the smart energy system to be successful in Denmark, there are some key infrastructural changes that are required on the supply side, which include the following:

- Increase of district heat share of heating from 53 to 63% with focus on low-temperature district heating.

- Integrating renewable energy, such as wind power, with heat pumps at district heating level and building level.
- Utilising wind power to produce and store heat in large-scale thermal storage for district heating.
- New heat sources are used in district heating, such as heat from solar thermal sources and non-conventional excess heat sources (geothermal heat, solar heat, excess industrial heat).
- Electric vehicles consume renewable electricity; rail is completely electrified, as well as some light freight.
- Electrofuels (liquid and gas) are produced via electrolysis and other technologies to integrate renewable electricity and to store electrical energy in areas where it is not traditionally stored (e.g. heavy transport liquid fuels).

In summary, the smart energy system is deemed the most feasible way to achieve a sustainable 100% renewable energy system in Denmark, and it will cost about the same as the system today (Mathiesen et al. 2015a).

Latest research on smart energy systems

This paper utilises data from the most recent study on the smart energy system in Denmark called the “IDA Energy Vision 2050” completed in 2015 by Aalborg University for the Danish Society of Engineers (Mathiesen et al. 2015a). This latest study was an update from previous iterations, and it included updates for technology costs, technology developments and changing demographics.

The main scenario from the IDA Energy Vision 2050 is used in this paper, and is referred to as the “IDA 2050 scenario”. The IDA 2050 scenario provides the energy system configuration in 2050, and the scenario will be used to demonstrate how the country will transition to 100% renewable energy and to assess new buildings within this context. This assessment will help demonstrate the impacts of new buildings being modelled in the future energy system.

The main energy quantity changes for demand and supply in the energy system from 2015 to 2050 are presented in Table 2.

As the system transitions to a smart energy system from 2015 to 2050, the primary energy demand of the energy system decreases, even though the electricity demand increases (Fig. 3). This demonstrates a significant improvement in the energy efficiency of the system. This is due to more efficient technologies, such as renewable electricity, electric mobility and an increase in cross-sector integration and energy storages, for example utilising wind power in district heating and reducing the use of solid fuel technologies, such as power plants, CHP and boilers.

Table 2 Main energy system demand and supply changes from 2015 to 2050 (Mathiesen et al. 2015a)

Energy component	Year	
	2015	2050
Electricity demand (TWh)	34	93
Buildings heat demand (TWh)	47	35
Offshore wind production (TWh)	4.4	64
Onshore wind production (TWh)	7.2	16
Solar PV production (TWh)	0.6	6.4
Fossil fuel consumption (TWh)	155	0
CHP + PP production (TWh)	21	14
District heating supply (% of total heat demand)	53	63

Impact of new buildings on the future Danish energy system

The second part of this paper looks at the total and average heat demand of the building stock that is likely to exist in 2050. The purpose is to analyse the impact of the heat demand of new buildings built to 2050 in the context of the renewable energy system.

This section will firstly describe the heat demand of the building stock modelled in the IDA 2050 scenario. Then in the second part, the heat demand of the new buildings will be analysed with lower heat demands to understand the impact on the renewable energy system. This will demonstrate the impacts from new buildings.

The Danish building stock in the 100% renewable energy system

The “building stock” in Denmark as defined in this paper, includes residential and service (office) buildings (this excludes hospitals, schools, hotels, retail, and sport buildings, which account for around 15% of total building floor space) (Wittchen et al. 2016). These other buildings were excluded due to lack of data. Despite this, the building stock that is included accounts for the majority of the heat demand in the building stock (it is assumed that heat demand linearly correlates with heated floor space), and this means the results and conclusions remain valid. The building stock in 2050 will include the floor space of the existing building stock in 2015 plus the floor space of new buildings added from 2015 to 2050. This is described below.

Building stock heated floor space in 2050

In 2015, the total heated floor space for residential and service (office) buildings was 358 million m². Eighty-four percent of the building floor space is residential and over 50% consist of detached single-family houses (Wittchen et al. 2016). On average, 0.25% of the existing buildings are demolished and replaced per annum (Energi- Forsynings- og Klimaministeriet 2014). For the buildings replaced from 2015 to 2050, it is assumed that they are replaced with a building with improved heat demand, and consequently, the average heat demand of the existing building stock will be reduced by this new building.

From 2015 to 2050, the total predicted new building floor space is 113 million m², which is a new build rate

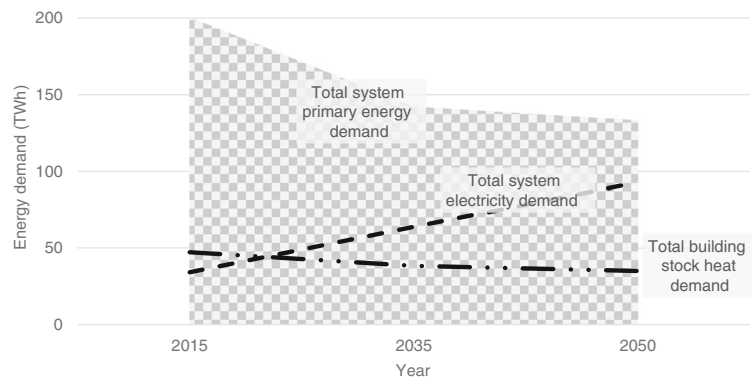


Fig. 3 From 2015 to 2050, the figure shows the correlation between total primary energy demand of the system and the total electricity demand of the system as well as total heat demand of the

building stock. The improved energy efficiency and synergies between the energy sectors within the system cause the primary energy demand to decrease over time

of approximately 1% per annum (Danish Energy Agency 2014). The proportion of new building floor space built to 2050 as residential and service (office) buildings is assumed to be kept at a similar proportion that exists today of 85 and 15%, respectively.

Overall, in 2050, the total heated floor space of the building stock is expected to increase to 461 million m².

Building stock heat demand in 2050

In 2015, the average heat performance of the existing buildings was 132 kWh/m², including hot water. In the IDA 2050 scenario, the existing building stock was assumed to be renovated to a point where the heat demand is reduced by 40% from 2015 to 2050. Thus, the average end-use space heat demand lowers from 132 to 80 kWh/m². The hot water demand remains the same (hot water uses 14 kWh/m²). These heat savings are based on future cost-effective renovation measures that could be achieved in the next 35 years (Lund et al. 2014b). New policy measures would be needed to encourage these renovations and retrofits. For instance, policies could be introduced to subsidise renovations for poorly performing buildings. Furthermore, for users that are connected to district heating, to encourage heat savings by the user, the heat tariffs could be modified. Currently, district heat tariffs are based on a large proportion of fixed tariff which pays for the long-term investment in infrastructure for production, storage and distribution (Meyer et al. 2014). The fixed share of the heating tariff could be made all or more as variable, thus encouraging consumers to consume less heat.

By lowering the total heat demand of the existing buildings, this helps to (1) lower the peak heat demands

needed from heating technologies, which allows new technologies into the mix; (2) supply thermal energy at lower temperatures via low-temperature district heating; and (3) increase the retention of heat in the building envelope, which allows for more flexible heat supply. These improvements enable a new possible configuration of the energy system in the future. New technologies can be implemented, which enables the system to be less expensive and consume less biomass (Mathiesen et al. 2016).

In this paper, the heat demand of the new building stock is the main factor being analysed for new buildings. For new buildings being built in 2015, the heat demand was around 56 kWh/m² (42 kWh/m² for space heating and 14 kWh/m² for hot water), which was based on the trajectory of heat demand improvements since 2005 (Wittchen et al. 2016; Mathiesen et al. 2015a; Lund et al. 2014b). In the analysis of the 100% renewable energy system, for new buildings built to 2050, it was assumed in the IDA 2050 scenario that this heat demand remains constant from 2015 onwards based upon cost analysis at the system level (Lund et al. 2014b). The main aim of this paper is to analyse the impacts on the energy system when the heat demand of the new buildings is reduced lower than this level in order to achieve nZEB status.

Table 3 presents the key main areas in which the total Danish building stock is expected to change in order to aid the future energy system in 2050. Key areas are shown for the buildings in 2015 and in the future energy system in 2050. The table shows that at the building level, the expected flexible demand is very limited: on-site electricity production and own use is very limited, and on-site electricity storage is very limited. These

Table 3 Three key areas in which the Danish building stock will be involved in the future 100% renewable energy system (Mathiesen et al. 2016)

Energy efficiency element	Building element	Magnitude in 2015	Magnitude in 2050
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

conditions are required in order for the energy system to be built and function effectively in order to be low-cost and consume sustainable amounts of biomass.

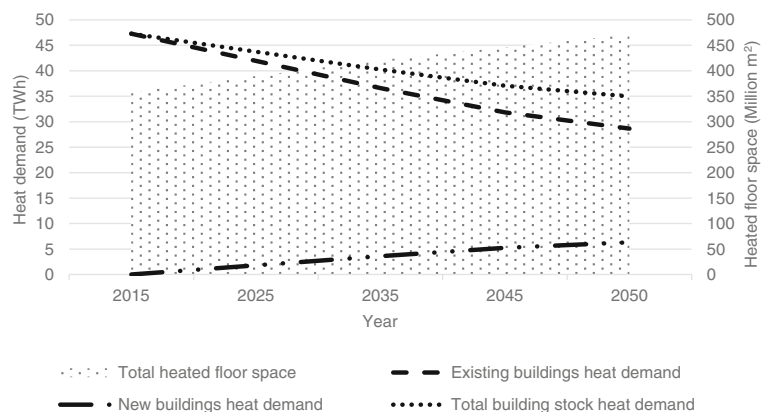
The total heat demand for existing buildings, new buildings and the entire building stock in the IDA 2050 scenario is shown from 2015 to 2050 in Fig. 4. The heated floor space of the total building stock is also shown. This data is based on an expected trajectory and would need to be updated over time to maintain its accuracy, but it is not expected that this trend would change significantly in the future.

The figure demonstrates that the change in the total heat demand of the entire building stock is very closely aligned with the heat demand of the existing building

stock. This is due to the large size of the existing building stock and its high heat demand. The new buildings make up a relatively small proportion of the total heat demand but slowly gains significance over time. In 2035, the new buildings would account for around 9% of the total heat demand in the country and 18% of the total heat demand in 2050.

Lowering the end-use heat demand in the building

In this section, the impact on the energy system from decreasing the heat demand of new and existing buildings is investigated. nZEBs depend on low end-use energy demand, and the heat demand is the largest

Fig. 4 Total heated floor space and total heat demand of existing, new and total building stock in Denmark from 2015 to 2050

component of the net primary energy demand of a nZEB; thus, it makes sense to investigate it being reduced.

Scenarios for reducing heat demand of the building stock

Six scenarios were analysed in which the average heat demand of the existing buildings (2015) and future buildings (built from 2015 to 2050) were adjusted. The heat demand from 2015 to 2050 (i.e. renovation/retrofit rate for existing buildings) is adjusted linearly. The electricity demand of the new buildings was not included since most of the building floor space is expected to be residential and only the electricity from building operation is relevant in the nZEB calculation for these buildings and this is expected to be a small energy demand. It is expected that heat pumps will have a high proportion of heat supply (32%) in the future building stock in 2050. Despite this, the total electricity demand would be approximately 2 TWh, which is a small proportion of the total energy demand of the building stock (< 5%) and the energy system (< 2%). For the existing buildings, the heat demand was analysed for two heat demand levels in order to demonstrate the importance of the existing buildings in the future energy system and to demonstrate the significance of the new building heat demand level in this context. The scenarios were as follows:

Scenario (1) From 2015 to 2050, no further renovations are made to the existing buildings; thus, they continue to have an average heat demand of 132 kWh/m². All new buildings are built with an average heat demand of 56 kWh/m²

Scenario (2) From 2015 to 2050, no further renovations are made to the existing buildings; thus, they continue to have an average heat demand of 132 kWh/m². All new buildings are built with an average heat demand of 36 kWh/m²

Scenario (3) From 2015 to 2050, all new buildings are built with an average heat demand of 56 kWh/m². The average heat demand in existing buildings is reduced by 40%, decreasing to 80 kWh/m².

Scenario (4) From 2015 to 2050, all new buildings are built with an average heat demand of 44 kWh/m². The average heat demand in existing buildings is reduced by 40%, decreasing to 80 kWh/m².

Scenario (5) From 2015 to 2050, all new buildings are built with an average heat demand of 36 kWh/m².

m². The average heat demand in existing buildings is reduced by 40%, decreasing to 80 kWh/m².

Scenario (6) From 2015 to 2050 all new buildings are built with an average heat demand of 56 kWh/m². The average heat demand in existing buildings is reduced by around 60%, decreasing to 54 kWh/m².

In each scenario, all the new buildings built from 2015 to 2050 have on average one of these heat demand levels, i.e. in Scenario 2 all the new buildings have an average heat demand of 44 kWh/m². This means some buildings consume more heat and some consume less. The new buildings are assumed to be built following a linear growth from 2015 to 2050. The mix of building types is the same as today which consists of 15% service (office) and 85% residential buildings.

As the total heat demand for the buildings is adjusted in each scenario, this means that the heat demand of the entire building stock will change and thus the capacity of the heat supply technologies in the system need to be adjusted to meet the altered demand. This is included in the study by adjusting the size of the heat supply units according to the new heat demand they need to meet.

The technologies in the energy system that were adjusted according to the total heat demand in the scenarios include the following:

- Centralised boilers that supply district heat to the buildings.
- The capacity of the district heating network.
- Individual boilers in the buildings.
- Individual solar thermal in the buildings.
- Individual heat pumps in the buildings.

Although the total heat demand is adjusted, the proportion of heat produced from different technologies for the new building stock for each scenario will remain the same as in the IDA 2050 scenario, since it is assumed these proportions are optimal for the renewable energy system. This means that when the total heat demand is adjusted, each of the heat supply technologies are adjusted in equal measure to one another. The proportion of heat delivered from each technology is presented in Table 4.

To achieve a lower heat demand, additional investment costs are required for the renovation of existing buildings and for the improvement of new buildings. These costs were based on Lund et al. (2014b). The

Table 4 Proportion of heat delivered from each technology

	Proportion of total heat supply in building stock in 2050
Heat pump at building level	32%
Solar thermal at building level	6%
District heating	59%
Biomass boiler at building level	3%
Total	100%

investment costs for renovating existing buildings are calculated in the following way. The costs are less in the beginning due to renovating older poorly performing buildings and after the older buildings have been renovated and newer ones start being renovated the costs increase.

Investment costs for new buildings are based on lowering the heat demand level of a new 150-m² single-family house by adding new technologies. The investment costs for all new buildings are based on this exemplar.

The investment costs for the heat supply technologies in the energy system are calculated by either increasing or decreasing the costs according to the change in capacity of the heating units. The costs are sourced from the EnergyPLAN Cost Database which includes updated cost data from the Danish Energy Agency (Aalborg University 2017).

Analysis software: EnergyPLAN

For each scenario, the energy system needs to be balanced to sufficiently supply energy in every hour during the year. Therefore, an analysis of the energy system for each scenario is required, and this was done using the simulation software EnergyPLAN (Aalborg University 2010). EnergyPLAN simulates the energy system on an hour-by-hour basis by integrating the different energy sectors, including electricity, heating and cooling, transport, industry and gas. The tool balances the system with support from a number of technical or market regulating strategies defined by the user. The investment, operation and maintenance costs are included for all the energy supply technologies.

The entire energy system which includes the building stock is modelled for the year 2050. To compare the scenarios, the relevant outputs from the tool are total

heat demand of the building stock, total biomass demand and total socio-economic cost for the energy system and improving the building stock.

Biomass is expected to be the main solid fuel in 2050, and it will be in limited supply in Denmark and globally. Over the past decade, numerous analyses have been carried out on the availability of sustainable biomass in Denmark, for example by the Danish Energy Agency and the Danish Commission on Climate Change (Danish Energy Agency 2006; Danish Commission on Climate Change 2010). Further analysis was done in Lund et al. (2011). The Danish Commission on Climate Change found that the main biomass sources will be residual from agriculture and forestry, but the country could also use algae and biomass crops. However, algae is not viable on a large scale at present and energy crops would be in competition with food production. Furthermore, it is expected that only 75% of the available biomass will be available for energy since it will be in competition with other bio-based industries (i.e. bioplastics).

On average, all the studies point to the total available sustainable biomass (residue biomass) in Denmark to be approximately 45 TWh considering impacts on food production, biodiversity and security of supply. Including energy crops and algae, the potential is increased to 60 TWh (Mathiesen et al. 2015a). However, as explained above and stated in these studies, a sustainable and reliable consumption would be at the lower end of this range. Therefore, it is important to understand how much biomass is needed in each scenario.

Results

The results for the different scenarios are presented in Table 5 and Fig. 5.

The results show that although new investments are made to renovate existing buildings and to improve new buildings, the total system costs do not change significantly within each scenario. The difference in cost for the heat supply units actually counteracts the increased or decreased building costs. For example, scenario 3 has high renovation costs for existing buildings (over 1 billion euro per year); however, it has the lowest total system cost of all the scenarios due to smaller heat supply units. However, as more money is invested to improve the new buildings in scenario 2, 4 and 5, the total system cost increases.

Table 5 Total heat supply for the building stock, the biomass demand and the total annualised socio-economic costs of the building stock improvements and of the energy system for each of the six scenarios in 2050

	Scenario 1—exist.: 132/new: 56	Scenario 2—exist.: 132/new: 36	Scenario 3—exist.: 80 / new: 56	Scenario 4—exist.: 80/new: 44	Scenario 5—exist.: 80/new: 36	Scenario 6—exist.: 54/new: 56
Total heat demand (TWh)	53	51	35	34	33	26
Biomass demand (TWh)	52	52	46	46	46	45
Additional annualised cost to renovate existing buildings (M€)	0	0	1136	1136	1136	2026
Additional annualised cost to improve new buildings (M€)	0	523	0	282	523	0
Total energy system costs	22,197	22,502	22,137	22,283	22,471	22,458

Although scenario 1 and scenario 2 have relatively low costs, they have the highest heat demand of 53 and 51 TWh, which also leads to the highest biomass demand of 52 TWh in each scenario. This is because the existing building stock is not renovated from 2015 to 2050, maintaining an average heat demand of 132 kWh/m². The biomass demand can be considered unsustainable, since it is very close to the upper limit of sustainable biomass potential in Denmark, and this would require new bioenergy sources, such as energy crops and algae or imported biomass. Scenario 2 is a worst-case scenario since the heat demand of existing buildings will improve over time as it is already.

In scenario 3, the heat demand is reduced substantially from 53 to 35 TWh; it has the lowest system costs. Scenario 3 also has the one of the lowest biomass demands of 46 TWh, which is near the sustainable level of biomass consumption. It involves renovating the existing buildings to an average heat demand of 80 kWh/m²; new buildings have an average heat demand of 56 kWh/m².

In scenario 4 and scenario 5, the biomass consumption does not decrease significantly as the new buildings are improved to 44 and 36 kWh/m², respectively. This is because the total heat demand decreases by only 1 and 2 TWh, respectively.

In scenario 6, the heat demand of the existing building stock is decreased to its lowest level of 54 kWh/m² (around 60% reduction from the original level of 132 kWh/m²) and new buildings remain at 56 kWh/m². This decreases the total heat demand to 26 TWh. Despite this decrease, the biomass demand does not decrease much further and this is due to the configuration of the energy system. In the IDA 2050 scenario, there is a significant amount of waste heat delivered from industry to the district heating system. This waste heat will mostly be generated by renewable electricity and supplied at a constant rate. Although there will be efficiency gains in industry which could lower the waste heat supply, new sources of waste heat are expected to be made available for example from synthetic fuel production (i.e. from electrolyzers) and new industries such as data centres. Therefore, there is minimal reduction in biomass demand from the reduced heat demand. There is actually an oversupply of heat from these sources in this scenario because the heat demand has reduced too far. This also means that the capacity of

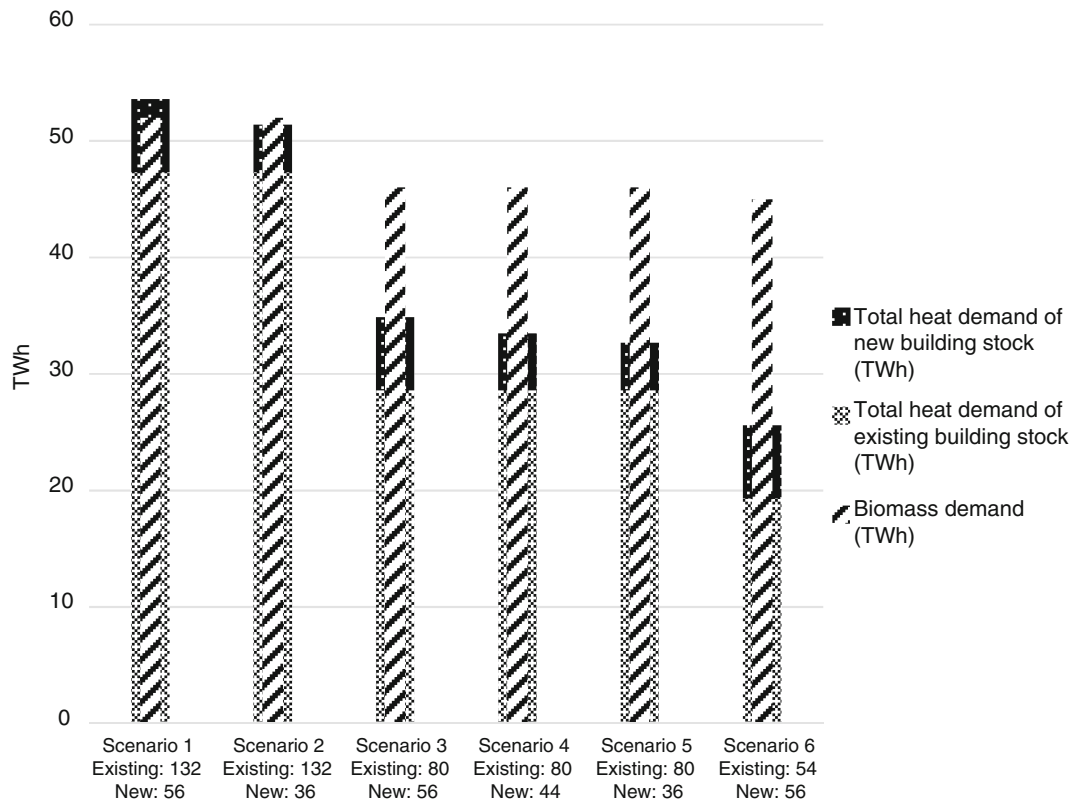


Fig. 5 Total heat demand and biomass demand of existing and new buildings in 2050 in the six scenarios

heat technologies are not reduced which leads to a minimal cost saving.

Based on the analysis above, it appears that retaining the new building heat demand at around 56 kWh/m^2 is suitable for the transitioning energy system based on cost and biomass consumption. Retaining this heat demand does not cause problems for the energy system, and when this value is decreased further, it does not deliver additional benefit to the system in terms of cost reduction or biomass reduction in the renewable energy system.

Applying heat supply primary energy factors

In the future energy system, the configuration of the heat supply is expected to be known, since the design the energy system needs to be planned to achieve this. Therefore, this allows for the quantification of the primary energy of the heat supply in the new building stock. Thus, in this section, the primary energy factors are applied for the supply of heat to the new buildings in order to understand their impact on net primary energy demand of the buildings.

The primary energy factor for the energy carriers will change over time as the system improves. To define the primary energy factor for the new buildings in this paper, the simplest approach is taken which is to calculate the net primary energy demand of the new building stock based on the primary energy factors in 2050. In the current system, it is easier to quantify the primary energy factors because the system is based on individual sectors dependent on fuels. But within the future renewable energy system, the numerous interactions between energy sectors makes the calculation very complex; therefore, a best estimate is made here.

Biomass has a primary energy factor of 1, and this contributes to the primary energy factor for district heating and electricity in 2050, whereas all other energy carriers will have a primary energy factor of 0. Based on the energy mix in 2050, the estimated primary energy factors based on the biomass consumption are presented in Table 6. The primary energy factors are calculated based on the results from EnergyPLAN. EnergyPLAN includes all the elements of the energy system which includes heat losses in district heating pipes (20%) and losses from thermal storage, as well as conversion losses

Table 6 Primary energy factors for energy carriers in 2050 based on the IDA 2050 scenario

Primary energy factors	2050 (derived from 2050 energy system)
Electricity	0.2
District heat	0.3
Biomass	1

of heat units (i.e. boilers). The primary energy factor is determined by the total biomass consumption to produce a unit of district heat and electricity in 2050.

The production of heat for the new building stock is from different heat supply technologies in the IDA 2050 scenario. This is shown in Table 7. This table also shows the total heat delivered from each heat technology to the new buildings. These values were determined by using the average heat demand value of 56 kWh/m², which was used in scenarios 1, 3 and 6. Furthermore, the table shows the amount of primary energy (for heating) that all new buildings will consume in 2050.

The total primary energy demand (from heating) is 1.4 TWh for the new building stock in 2050. The total new building stock is predicted to have 113 million m² heated floor space; therefore, the average primary energy demand (for heating) for all the new buildings is around 13 kWh/m² ((1.1 TWh/113 Mm²) × 1000 = 13 kWh/m²).

Using the same calculation procedure, the average primary energy demand (from heating) for the six scenarios is shown in Table 8.

The results show that when new buildings are built with an average heat demand of 36 kWh/m², the

average primary energy demand is 8 kWh/m². However, as discussed above, at this level, the energy system does not achieve greater cost reductions or biomass reductions. The only benefit is that the net primary energy demand of the building is lower.

Discussion

The configuration of the Danish energy system today and in the future 100% renewable energy system has an important influence on the design and role of new buildings. Firstly, Denmark has a highly efficient heating system due to the 53% share of district heating. This is expected to increase to 63% in 2050. The district heating system provides opportunities for integrating more sustainable energy technologies into the system, which includes low-temperature district heating, heat pumps, industrial and geothermal heat, and solar thermal and thermal storage. As these technologies are integrated into the system, the levelised cost for supplying heat is likely to decrease as well. Secondly, the existing buildings will account for most of the heated floor space, and most of the heat demand of the building stock in the future energy system in Denmark in 2050. The paper has demonstrated the importance of this building stock in the future energy system, which is related to the size of the heat demand today and in the future. If the existing buildings are renovated sufficiently (from an average heat demand of 132 to 80 kWh/m²), the 100% renewable energy system will achieve lower system costs and sustainable biomass demand. Therefore, for new buildings, the need for lowering the heat demand and integrating local renewable energy is less certain in this context.

Table 7 Heating technologies, total heat supply from each technology, primary energy factors for energy carriers and primary energy demand for the new building stock built in 2050

	Proportion of total heat supply in new building stock	Total heat delivered from each heating technology (TWh)	Primary energy factor for energy carrier for 2050 (kWh)	Primary energy demand for 2050 (TWh)
Heat pump	32%	2	0.04 (heat based on electricity ¹)	0.09
Solar thermal	6%	0.4	0	0
District heating	59%	3.7	0.3	1.1
Biomass boiler	3%	0.2	1	0.24
Total	100%	6.3	n/a	1.4 (13 kWh/m ²)

¹ The heat pump technology has a Coefficient of Performance (COP) of 4.5 in 2050

Table 8 Total heat demand and primary energy demand for heating for each of the six scenarios in 2050

	Scenario 1—exist.: 132/new: 56	Scenario 2—exist.: 132/new: 36	Scenario 3—exist.: 80/new: 56	Scenario 4—exist.: 80/new: 44	Scenario 5—exist.: 80/new: 36	Scenario 6—exist.: 54/new: 56
Total heat demand (TWh)	53	51	35	34	33	26
New building average primary energy demand (from heating) (kWh/m ²)	13	8	13	10	8	13

Implications for Denmark and other European countries

Specific policy instruments for energy efficiency in buildings in Denmark and other European countries are directed by the EPBD and national building codes. Denmark has specific policy initiatives for new and existing buildings (i.e. for existing buildings the rules are strict about the characteristics of replaced buildings elements). However, as demonstrated in this paper, increasing energy efficiency in the built environment and the impact on sustainability, such as reducing carbon emissions, needs to be understood in a broader context. Isolated policy initiatives are not sufficient in scope. To understand the specific policy initiatives, the entire energy system should be understood. The building stock is mostly located in cities and municipalities, and thus, the buildings are affected by local plans and policies. Therefore, it is not possible to discuss policy initiatives without thinking about them in context of what they are for and about their strategic aim.

Sperling et al. (2011) found that for Denmark to achieve a 100% renewable energy system, which includes reducing energy demand in the built environment, policy decisions should be made based on a strategic energy planning approach at the municipal level. It should be underlined that strategic municipal energy planning should address all sectors of the energy system and be based on an integrated understanding of the energy system. By following this approach, it could provide a robust framework for making policy decisions and actions for the new and existing buildings. The approach consists of five main components being (1) a national 100% renewable energy system planning strategy that is long-term and which defines specific targets and milestones, (2) a framework for strategic municipal energy planning which distributes tasks in a clear way, (3) technology and activity specific legislation and support schemes, (4) strategic municipal energy plans that define clearly which roles municipalities should play in a

100% renewable energy system and that state that municipalities become the responsible authorities for planning and implementing the energy plan at the local level, and (5) implementation of strategic municipal energy plans. Furthermore, Sperling et al. (2011) explains that strategic energy planning should clarify what types of analyses and/or modelling tools the drafting of a municipal 100% renewable energy plan should be based on. Analytical tools, such as EnergyPLAN as used in this paper and a Heat Atlas can support the design of local 100% RES in an integrated way, but a number of other tools may be applicable for the task (Connolly et al. 2010, Mirakyan 2013).

By following a strategic approach in Denmark, some specific policy ideas for renovating existing buildings have already been suggested by Meyer et al. (2014), whom looked at the barriers and solutions for energy renovation in Denmark within the framework of strategic thinking. Meyer et al. (2014) suggest an incentive system, which consists of three interacting components being (1) energy consultants, (2) energy reports and (3) investment subsidies. Some specific suggestions include, low interest rate loans based on an energy report from energy consultants where investment subsidies are worked out by the energy consultants to get a precise description of the requirements to move a house a specified number of places up on the scale of energy efficient houses. In addition, incentives could be made available to energy upgrade while other renovations are taking place, such as replacing a roof, which is shown to be most cost effective. Tax deductions could focus on energy savings (measured) which is combined with incentives. Tax could be graduated in accordance with the energy intensity of a house creating a strong influence on new investments for energy efficiency. Smart meter data for electricity and district heating consumption and smart thermostats could be used to help achieve renovating existing buildings according to their needs (Meyer et al., 2014).

These are just a few suggestions that could be implemented which are based upon detailed analysis of the energy system needs and strategic thinking.

User behaviour

This study uses theoretical energy demands expected to be achieved in the future energy system, but it is known that the behaviour of building users can lead to differences from the theoretical demands (Gram-Hanssen 2013). User behaviour and energy consumption is often dictated by three particular elements which are described by Gram-Hanssen (2015) being (1) knowledge of the user, (2) user norms (meanings) and (3) user habits. Therefore, to lead to desirable outcomes when trying to achieve energy savings with renovations/retrofits, these three elements should be considered in combination together.

Policy initiatives should be based on the latest social science research around influencing these elements. Basic approaches include looking at how the buildings and new technologies change user-practice and vice-versa (Vlasova & Gram-Hanssen 2014). Shove (2003) describe how the three factors are largely formed through social norms and cultural and economic factors; therefore, further research should be placed on these areas to identify how they impact the energy consumption.

Future research

Based on the uncertainty around user behaviour and energy demands, sensitivity analysis should be done to test higher energy demand levels than were tested in this paper, in order to understand the short- and long-term implications in the energy system.

This study is based upon a long-term analysis (to 2050) and it used an energy system in 2050. A shorter-term analysis could be useful to supplement the study to investigate the shorter-term impacts of new buildings. The energy system in 2030 could investigate the mix of old technologies and new technologies and the intermediary impacts of new buildings in this context. Despite this, in the near future (i.e. over the next 10–20 years), it is expected that the energy system is able to accommodate the heat demand of new buildings because the new heat demand would still be low in comparison to the existing buildings.

This paper did not investigate the implications from installing local renewable energy nearby the new

buildings. However, the system described in this paper depends on sharing energy resources; therefore, it is expected that these types of buildings would need to operate in cooperation with the energy system needs. Therefore, their energy performance should be determined based on their contribution to the energy system as opposed to reducing their individual net primary energy demand. To quantify the beneficial contribution of new buildings to the energy system in terms of carbon emission reductions, or reductions in biomass consumption, a new calculation procedure that quantifies this could be useful.

Conclusions

The aim of this paper was to analyse the impact of new buildings in the Danish energy system as it transitions to 100% renewable energy. The impact when installing new low-energy buildings on the future energy system was assessed in terms of the change in total heat demand, resource demand (biomass) and the energy system socio-economic costs. The method assessed the future building stock, which includes new and existing buildings with different heat demands within the context of the future energy system configuration. Although this paper used Denmark as a case study, the applied methodology and the results are applicable in other European countries and it is recommended similar analyses are undertaken in other countries.

The paper showed that in the current and future Danish energy system, buildings built from 2015 to 2050 with an average heat demand of around 56 kWh/m² are sufficient. New buildings with heat demand below this level do not significantly decrease the total heat demand, biomass demand or energy system costs in the future energy system. This is due to the heat supply mix of the energy system today and in the developing 100% renewable energy system. The results indicate that the energy frames in Denmark after 2020 are arbitrarily low when considering the benefit the new low-energy buildings will provide to the system. The net primary energy demand for new buildings in Denmark should not be decreased by 25% every 5 years, reaching 0 kWh/m² in 2025. The current energy frames for new buildings in the Danish building code (BR15) are sufficient and therefore these levels should be maintained after 2020.

As shown in this analysis, by combining the new building stock and the mix of heat supply in the future energy system in 2050, the net primary energy demand (for heating) for new buildings is estimated at about 13 kWh/m² on average. This level is sufficient in the 100% renewable energy system, because at this level the energy system achieves a relatively low biomass demand, low system level costs and a highly efficient energy system. Today, based on current primary energy factors, 25 kWh/m² of renewable energy produced at a building aiming to achieve nZEB status can be deducted from the net primary energy demand of the building. If the heat demand of new buildings is maintained at the level today, this amount of renewable primary energy demand is sufficient to counteract building level primary energy demand. However, it has been shown that the cheapest options in Denmark for renewable electricity production are large-scale solar PV and on-shore wind, and these may not necessarily be built nearby new buildings (Mathiesen et al. 2017); therefore, options should be kept open about the location of renewable electricity. This study did not investigate the impact on the energy system from producing and exporting renewable electricity from new low energy buildings (i.e. nZEBs).

In terms of policy, with the design of the Danish energy system, policy should be designed to encourage energy savings in existing buildings, which will help to achieve sustainable levels of biomass consumption. Most of the future energy demand will be from these buildings and most savings can be achieved here; therefore, investments should be made into improving the existing building stock. The existing buildings should be renovated to achieve an average heat demand of around 80 kWh/m². Focus on existing buildings should be about achieving passive heat storage, via insulation and in new buildings as well. Not only will this make the energy system reduce energy demand but it will make it more efficient and more cost-effective since peak demands will be reduced when the heat production is spread across the day. It will also help the system integrate low temperature district heat and heat pumps.

The energy performance levels of new buildings should be based on understanding the contribution of new buildings to the transitioning energy system. Therefore, methods such as strategic energy planning described by Sperling et al. (2011) and the incentive system model as described by Meyer et al. (2014) could lead to more appropriate policies and actions. This

would help with determining the extent of energy savings required by the building stock but also if new buildings install nearby renewable electricity units, e.g. from solar PV, policies can focus on how exported electricity from these buildings can be utilised in the wider energy system and how the building owners can be reimbursed for this. In all European countries, the role of the buildings in the future energy system and the appropriate policies for the energy system transition need to be well understood and this requires a more comprehensive analytical and strategic approach to be applied.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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