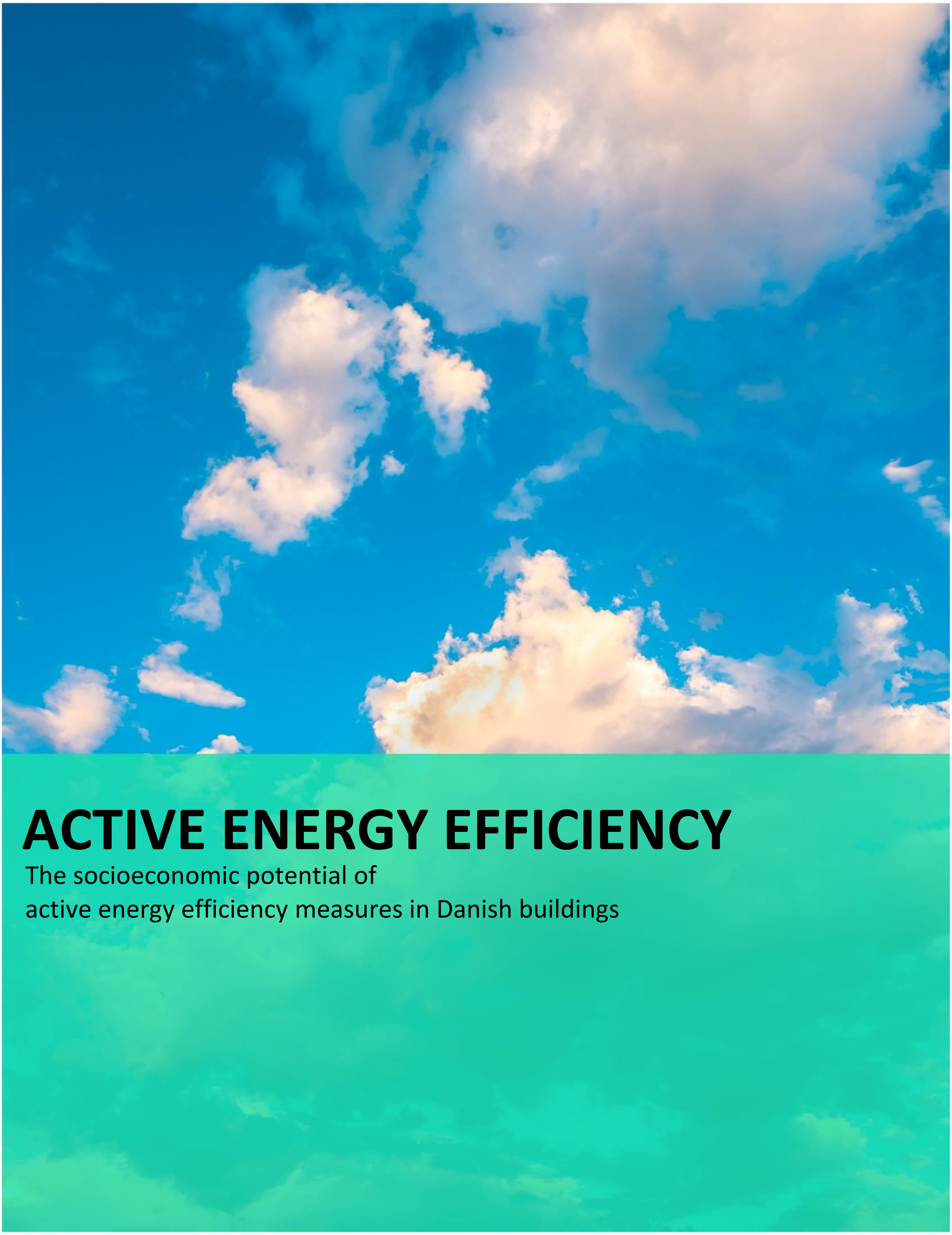
Ea Energianalyse



ACTIVE ENERGY EFFICIENCY

The socioeconomic potential of
active energy efficiency measures in Danish buildings

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1 Summary

The purpose of this analysis is to identify the socio-economic potential for energy savings through active energy efficiency measures in the Danish building stock towards 2030.

"Active energy efficiency" is defined as energy savings obtained through measuring, monitoring and control of a building's energy usage. This includes self-acting automatic control, digitalisation and automatization and the consequent use of data and information. An example of an active energy efficiency measures is a Heating, ventilation, and air conditioning (HVAC) control system, which based on monitoring and measuring of the surrounding conditions (e.g., the weather, the users of a room or indoor air quality), regulates the units under its control.

The scope of the analysis is the final energy consumption within households and commercial and public services. The analysed energy consumption was 224 PJ in 2019, of which 202 PJ was used for heating and hot domestic water (including 7 PJ electricity used for heating), and 22 PJ electricity used for lighting, cooling, and ventilation in the commercial and public services. The remaining electricity consumption of 45 PJ, which is mainly used in appliances and lighting in households, is outside the analysed scope.

The potential and economics of active energy efficiency are estimated based on a literature review and information from case studies received from the client. Unfortunately, in a Danish context, no systematic empirical studies have been carried out on the potential for active energy efficiency and therefore the results must be interpreted with caution.

The analysis indicates that even in a Danish context, where traditional mechanical radiator thermostats are widespread, active energy efficiency can deliver significant savings. We have identified the total potential for active energy efficiency measures to be 23 PJ in 2019, corresponding to a net saving of 10%. Existing policies and the expected effects going forward of the energy agreements in June 2020, only capture approximately 20% of the total potential from active energy efficiency towards 2030, leaving 80% on the table The non-achieved potential in 2030 is identified as 18 PJ or 8% of the overall, analysed energy demand by 2030. Most of the savings, 13 PJ, are related to heating and the remainder, 5 PJ, to electricity consumption (lighting, cooling, and ventilation).

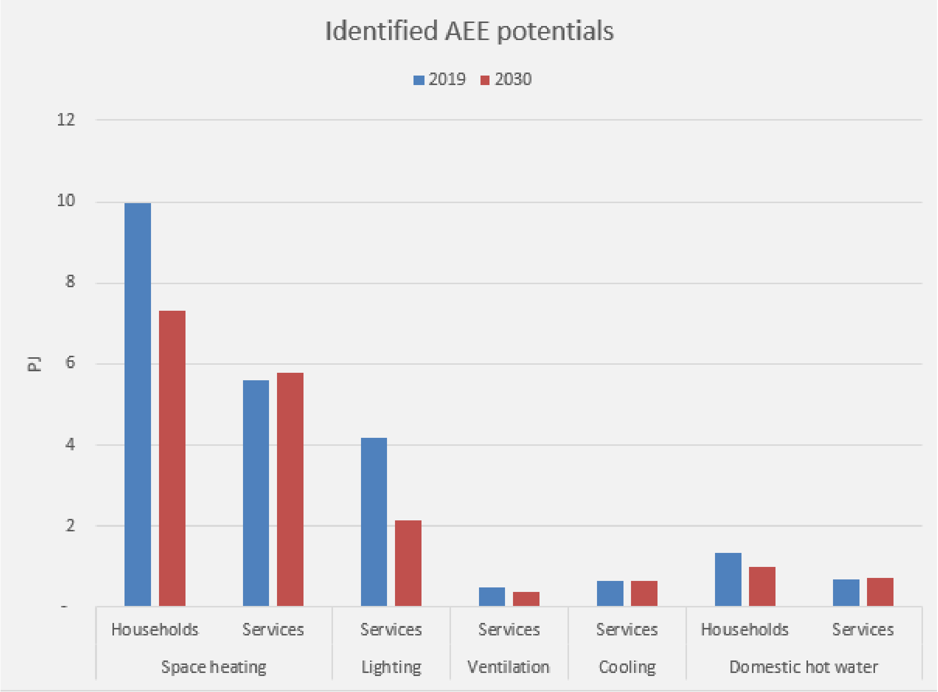

Figure 1: Identified active energy efficiency (AEE) potentials in 2019 and 2030. The 2030 numbers show the remaining potential in the absence of new policy measures.

Implementing the full potential for active energy efficiency measures is estimated to yield a socio-economic benefit of approx. 590 mill. DKK/annually (approximately 80 million EUR/annually) by 2030. The greatest potential lies within heating of single-family and multifamily households, followed by heating of commercial and public buildings and lighting of commercial and public buildings.

The financial benefits of energy savings mainly consist of a reduced need for production of energy and savings in energy infrastructure. It is assumed that most of the heat supply in 2030 is based on green energy technologies, in the form of district heating and heat pumps.

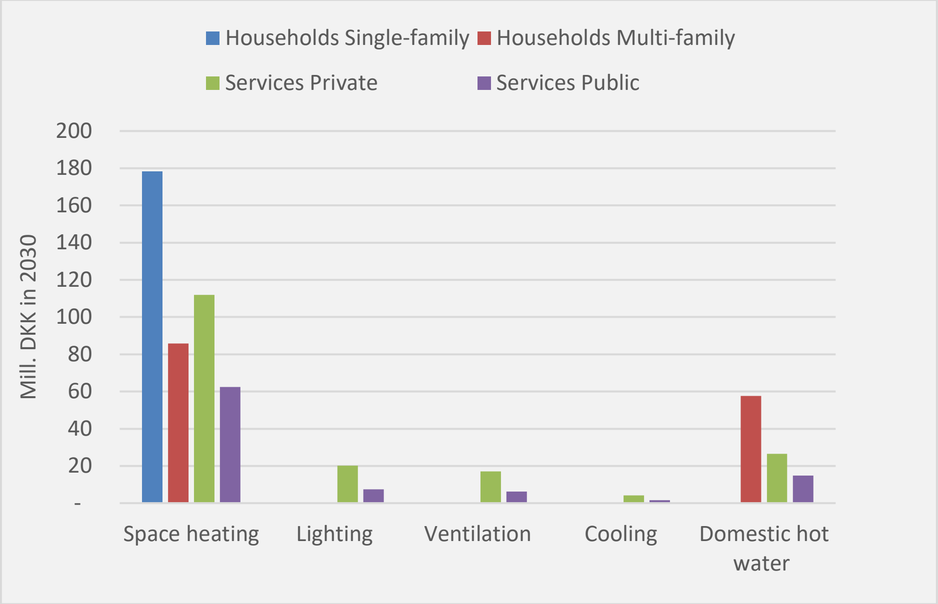

Figure 2: Socio-economic potential for energy savings by 2030

The project did not analyse which policy measures will be needed to achieve the savings identified. If it is possible to gradually implement the total active energy efficiency potential between 2022 and 2030, a greenhouse gas reduction of approximately 1.2 Mt CO_2 can be obtained over the same period.

Multiple-benefits from active energy efficiency measures

Active solutions and digitalization allow buildings to interact with the wider energy system enabling them to provide demand response to district heating and power systems. This may yield additional economic and environmental benefits through reducing the need for generation on expensive peak load units and by supporting more fluctuating renewable energy sources in the energy system.

Moreover, some active energy solutions allow building managers to monitor the moisture and CO_2-content of the air in the building giving them a tool to identify lacking indoor air quality and initiate adequate ventilation. The resulting benefits for society in terms of lower health expenses and increased productivity and learning are significant, see for example (Energianalyse, 2020).

Need for further analyses

It is recommended that further analyses are initiated to examine the potential for active energy efficiency measures in a Danish context based on empirical data for a representative portion of the building stock.

2 Introduction and background

The purpose of this analysis is to identify the socio-economic potential for energy savings through active energy efficiency measures in the Danish building stock towards 2030.

Objective

More specifically the objective of the analysis is:

1) To determine the savings potential of active energy efficiency measures in different types of buildings
2) and to quantify the economic, energy and CO_2-emission benefits of fulfilling this potential.

Ea Energy Analyses has previously examined the socio-economic potential for energy efficiency measures[1], but new knowledge and new framework conditions, including new climate agreements, recommendations and analyses presented by the climate partnerships[2], and a reassessment of the potential for active energy savings have meant that an updated assessment is relevant.

Definition of active energy efficiency

The analysis looks at the so-called active energy efficiency measures, where information, data and active management is key to reducing energy consumption (see definition in text box). Changes in the building envelope or other energy efficient solutions, which do not actively adapt their application to external conditions, are regarded as passive energy efficiency measures and not examined in this analysis.

Definition of active energy efficiency measures:
"Active energy efficiency" is defined as energy savings obtained through measuring, monitoring and control of a buildings' energy usage. This includes self-acting automatic control, as well as digitalisation and automatization and the consequent use of data and information. An example of an active energy efficiency measures is a HVAC control system, which based on monitoring and measuring of the surrounding conditions (e.g., the weather, the users of a room or indoor air quality) regulates the units under its control.

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[1] Ea Energianalyse, 2019: Analyse af det samfundsøkonomiske potentiale for energibesparelser

[2] In 2019 the Danish government established 13 climate partnerships with the business community to explore pathways and measures to reduce greenhouse gas emissions.

A graphical description of passive and active energy efficiency is displayed in Figure 3.

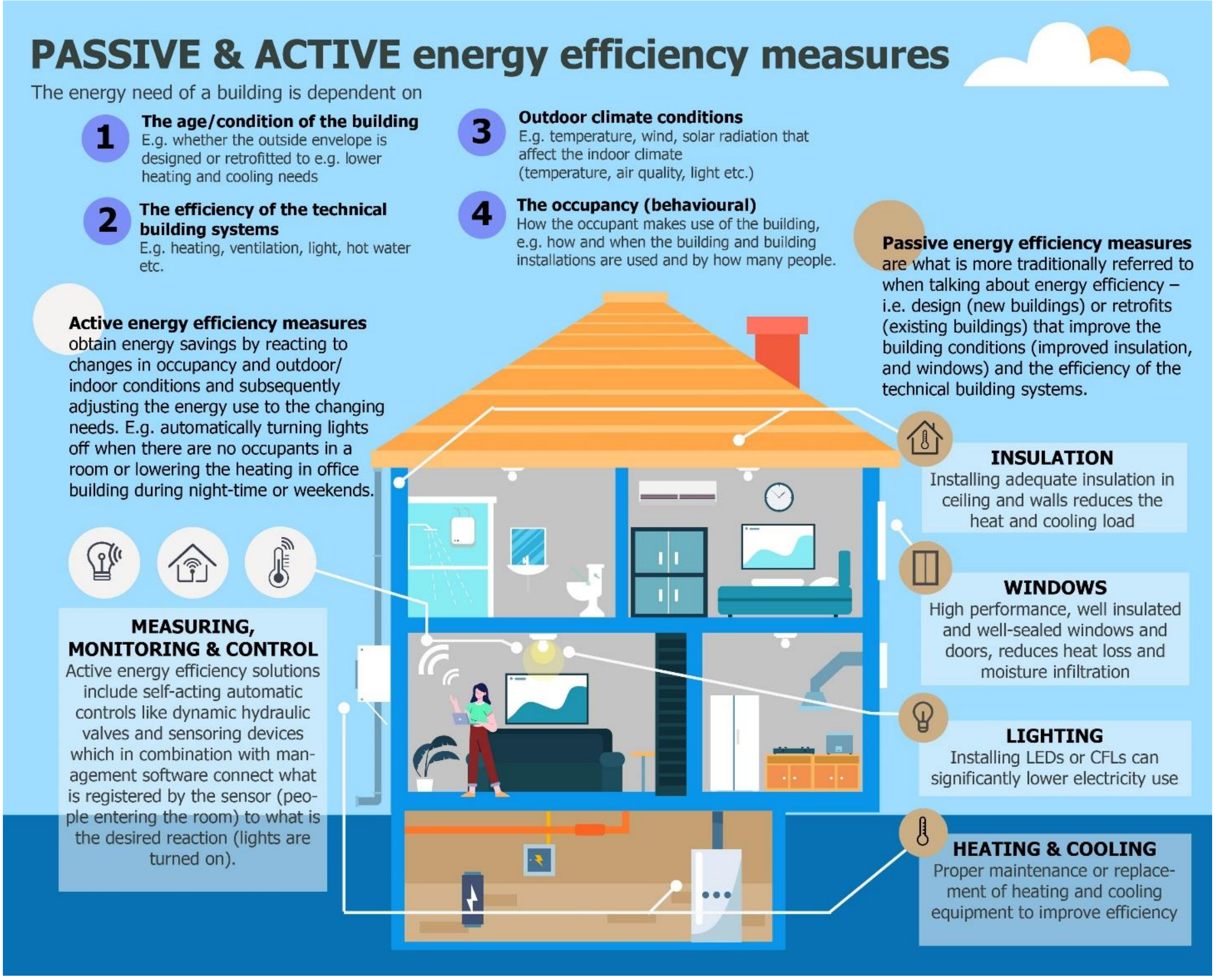

Figure 3: Graphical description of passive and active energy efficiency measures

Scope

This analysis is limited to the energy use and associated saving potentials within the final energy consumption for heat, domestic hot water, cooling, ventilation, and electric lights in buildings. For electric lights, only the electricity use in commercial and public services is analysed. Therefore, energy consumption for white goods, pumps and other appliances has not been analysed. Moreover, the analysis is limited to the final consumption of energy within households (divided into single-family houses and multi-family dwellings), commercial buildings and public buildings.

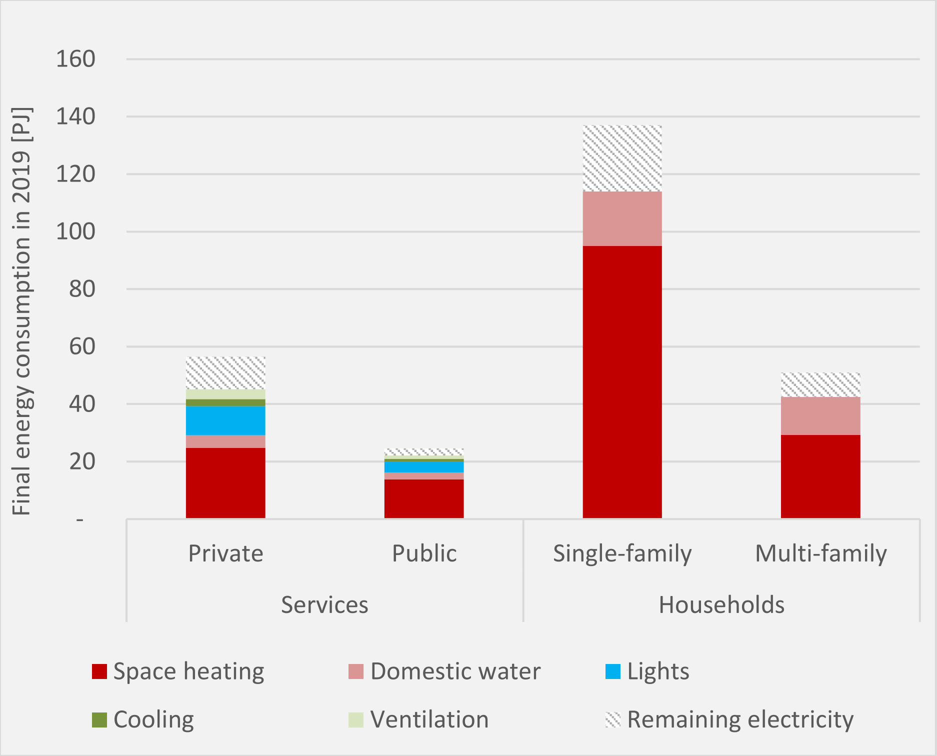

Figure 4: Building and building related final energy consumption in the analysed scope. Based on DEA Energy Statistic 2019 and distribution by Ea based on DEA Sparenergi, Green Transition Denmark and DEA Technology Data for Heating Installations.

The analysed final energy consumption was 224 PJ in 2019 of which 202 PJ was used for space heating and hot domestic water (including 7 PJ electricity used for heating), and 22 PJ electricity used for lights, cooling, and ventilation. The remaining electricity consumption of 45 PJ is outside the analysed scope.

The potential toward 2030 is evaluated against Denmark's Energy and Climate Outlook 2021[3] (DECO 2021) in order to identify the potential not fulfilled as a result of current policies. DECO 2021 shows a 55 % total reduction in greenhouse gas emissions by 2030 compared to 1990, meaning that current polices are 15 %-points short of complying with the Danish Government's 70% GHG reduction target. Electricity and district heating supply is assumed to convert to almost 100 % renewable energy towards 2030 according to DECO 2021 and CO_2 emissions reductions resulting from active energy efficiency measures are modest.

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[3] Energistyrelsen, 2021: Klimafremskrivning 2021

2.1 The interaction between active and passive energy efficiency measures

Energy savings achieved through active energy efficiency measures depend on the pattern of use of the building. The more variety there is in use and need over time, the greater the potential for savings through active measures, that adjust to changing conditions. The optimal level of energy savings, comfort and good indoor climate is therefore achieved in the interaction between passive energy savings such as better insulation and active control of heat, light, and ventilation.

The energy consumption for heating in buildings is typically closely related to the age of the building. Older buildings tend to have poorer insulation and a greater heat requirement per m^2. The relative and absolute energy savings of active energy efficiency measure are typically higher in poorly insulated buildings and therefore the attainable savings of an active energy saving measure in an old building depends on whether it has been renovated or not.

Passive energy measures, such as improved insulation, and active energy efficiency measures are different by nature. Passive energy efficiency measures require substantial investment, and typically they are only economically feasible when implemented as part of a general building renovation. Active energy efficiency measures entail modest upfront cost and often they offer attractive business cases on their own. Therefore, active energy efficiency measures represent an immediate potential, that may in principle be realised over a short time horizon, whereas the full economic potential for passive energy measures, need be implemented over 30 years or so.

2.2 The Danish building stock today

According to Statistics Denmark, there were a total of 4.6 million buildings in Denmark in 2020. Just above 37% are used for housing (including holiday homes), whereas commercial and public buildings (such as offices, warehouse, schools, hospitals) make up just under 4% of the total building stock (Statistics Denmark BYGB12, 2020). The remaining buildings are divided between a number of other categories not included in this study such as non-residential farm buildings, factories, other buildings used for production).

If, one looks at the area of the building stock (m^2), housing makes up 47%, whereas the offices and public building group makes up 18% of the total building area (Statistics Denmark BYGB34, 2020).

Further information on the Danish building stock can be found in Appendix B.

3 Identification of active energy efficiency measures

For each building segment the potential for active energy efficiency measures has been investigated within space heating and domestic hot water, ventilation and cooling, and lighting.

The analyzed measures range from simple control mechanisms, such as mechanical radiator thermostats to advanced systems with predictive controls.

To obtain an overview over the analysed measures they have been divided into layers varying from none to all, with additional layers for certain elements. The layer assigned **"All"** contains all identified active energy efficiency measure for the given element of energy use, which is considered the identified maximum potential.

Layer	Space heating (Single family)	Space heating (Services + Multifamily)	Lighting	Ventilation	Cooling	Domestic water
None	None	None	None	None	None	None
First	Mechanical radiator thermostats	Mechanical radiator thermostats	Motion sensors	Timers	Timers	
Second		+ Dynamic balancing		+ Demand control	+ Demand control	
All	Electronic radiator thermostats	+ MPC*	+ Daylight harvesting	+ Predictive control	+ Predictive control	MTCV**

*Table 1: Division of active energy efficiency measures into layers. *MPC: Model predictive control **MTCV: Multifunctional thermostatic circulation valves.*

Furthermore, it is assumed that transverse energy savings from central control systems and building management systems are included in the identified potential for each layer and element of energy use.

The identified potentials are based on a literature review and supported by case studies where available. It should be noted that the case stories often are "best-case" scenarios which are not necessarily representative of the entire building stock. For space heating, the **"First"** layer "Mechanical radiator thermostats" is already widespread today, why a level of prevalence for the individual layers have been used to identify the potential yet to achieve. For the identified level of prevalence see section 3.5.

Each section (space heating and domestic water, ventilation and cooling, lightning) starts with an overview of the energy use for the sector and the identified saving potential for the layer **“All”** i.e., the maximum potential for all measures and control system corrected for level of prevalence.

3.1 Space heating and domestic water

In 2019, the identified energy consumption for space heating was 162.8 PJ and the energy consumption for hot domestic water 39.0 PJ[4].

For space heating two layers have been identified for single family homes:

- Mechanical radiator thermostats (first layer)
- Electronic radiator thermostats (all-layer)

And three layers for multifamily homes and commercial and public buildings:

- Mechanical radiator thermostats (first layer)
- Dynamic balancing (second layer)
- Model Predictive Control (MPC) (all-layer)

For domestic water only one active energy efficiency measure has been analysed: Multifunctional thermostatic circulation valves (MTCV) (all-layer).

Based on the current level of prevalence of the different layers and the potential overlap between measures, the overall (maximum, all-layer) identified saving potential withing space heating and domestic water is:

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[4] The split between energy demand for space heating and domestic hot water is associated with some uncertainty.

Segment	Saving potential (Space heating)	Saving potential (Domestic water)	Energy use 2019 (PJ) (Space heating)	Energy use 2019 (PJ) (Domestic water)
Households				
Single-family	8%		95.0	19.0
Multi-family	9%	10%	29.3	13.2
Services				
Private	15%	10%	24.8	4.4
Public	15%	10%	13.8	2.4

MPC is only included for a portion of the multi-family house segment (approx. 20%) because the analyses indicate that the solution is only economically feasible for buildings with an above average heat demand. Apart from that, the above potentials assume full utilization of all identified active energy efficiency measures within space heating and domestic water including control systems and heat savings from demand-controlled ventilation and cooling.

It is important to stress that the potential at the individual building level can vary a lot.

For prevalence of technologies today, see section 3.5.

Due to its very high prevalence today mechanical radiator thermostats have not been further analysed.

Hydronic balancing

Hydronic balancing is a process that optimizes the distribution of water in a building's water-based heating or cooling system. The optimization is done through pressure-balancing in the different parts of the system, thereby achieving the desired indoor temperature in each individual section of the building, resulting in higher energy efficiency and reduced operating costs. Heating systems can be designed in different ways, but typically consists of a control program and a set of valves located at distribution points in the heating system. In a system of manual balancing, each valve in the heating system must be adjusted based on the design and calculation of flow rates, while the valves can be controlled automatically or intelligently by software in dynamic valve systems.

In unbalanced systems, parts of the system receive more water than they need, which might result in overheating, while reduced water flow to other parts of the system might result in difficulties in delivering enough heat.

Ensuring proper hydronic balancing is more important for larger and more complex heating systems found in multi-storey or larger office buildings, because single-family houses are relatively straightforward to balance due to the low number of radiators. In single-family houses balancing can typically be achieved simply by pre-setting the flow through the radiators, while larger heating systems require more advanced techniques and dynamic balancing.

Dynamic hydronic balancing

In a fully controlled system with dynamic hydronic balancing, the system automatically and dynamically adjusts to outdoor and indoor temperatures, and therefore continuously adjusts the pressure equilibrium in the system. A reference study conducted by Danfoss indicates that the final energy saving for an apartment building is 7% for manual hydronic balancing (in the starting point, but fades over time), and up to 10% for dynamic hydronic balancing (Osjnik, Kolb, Chambris, & Schramm, 2017).

The literature indicates that hydronic balancing of larger heating systems can result in heat savings of between 8% to 11% and as much as 15% for large older buildings, while the saving can be between 1% to 7% for single-family houses. These savings potentials represent static hydronic balancing, where the system is set up once for an average situation. (Schweikhardt, 2017) (Irrek, 2005) (Guzek, 2009) (Seifert & Meinzenbach, 2014)

Electronic radiator thermostats

Electronic radiator thermostats are analysed here based on their ability to replace mechanical radiator thermostats, which are the standard in many older buildings. Where a mechanical thermostat is typically controlled to retain a specified set heat level from 0 to 5 (corresponding to a set temperature level), electrical radiator thermostats can be regulated digitally without manually changing the thermostat. Electric radiator thermostats are typically also better at keeping the desired temperature level, and in addition to temperature level, they can also be set according to consumer behaviour, for example by lowering the temperature for fixed periods during the day, over a holiday period and turn off when windows are opened (either manually or in interaction with more advanced ventilation control). More advanced systems can automatically detect whether people are at home and map their usage patterns to optimize operations and increase the overall efficiency of the system.

Mechanical radiator thermostats are still widely used in Germany, among other places, where 94% of homes there had mechanical radiator thermostats in 2016. In a 2018 report it estimated that a similar figure was true for Denmark and other EU countries. (ECOFYS, 2016) (Viegand Maagøe, 2018). In the tertiary sector (commercial and public services) electric radiator thermostats are already today relatively widespread (Viegand Maagøe, 2018).

In the most recent Bolius homeowner analysis from 2018, about 13% of Danish households had replaced or planned to replace their older radiator thermostats with new radiator thermostats, while another 11% had considered replacing but had no timeframe in mind for doing so (Bolius, 2018). 75% answered that they had no plans for replacing their radiator thermostats, Thus, there is a great untapped potential for changing to electronic radiator thermostats in the Danish households.

Electronic thermostats can be applied in both singly- and multi-family buildings but often the upfront cost are not outweighed by the energy savings in apartments because the heat demand per household is typically lower. Therefore, in this study we have only considered electronic thermostates for single-family buildings.

Danfoss case on electronic radiator thermostats and control

In a case involving a relatively new family home of 163 m^2, Danfoss shows how a family was able to save as much as 28% of its heat consumption, when installing electronic radiator thermostats and a device to actively control heat demand based on time and use. The gains were achieved by lowering the temperature to 18° C during the day when the house was empty, and only increasing the temperature in the period 5 to 11 in the evenings of weekdays, and all day on weekends (Danfoss, 2014). To achieve this very high level of savings, it has been crucial to engage very actively and time-manage temperature and comfort levels, and the willingness to do so will therefore have a decisive impact on the realizable savings potentials.

More conservative estimates indicate savings ranging from 6 to 8% for electronic radiator thermostats (King, 2018). A major uncertainty with respect to the saving potential concerns consumer behaviour. According to a US survey from 2014 about 40% of programmable thermostat owners did not use the energy-saving programming features and in about one third of the homes, the occupants disabled or overrode the programming features (Marco Pritoni, 2015). Confusing interfaces was among other things blamed for the mal operation of the devices.

Heat uniform control systems

Just as radiator thermostats control the temperature level and heat flow by individual radiators, control can also be applied to the heating unit itself, adjusting and optimizing the flow temperature to the heating system to the circumstances and needs. In particular, the control unit will save energy by compensating and adjusting the flow temperature to match the outside temperature and by setting the heat requirement according to time, so that, for example, the heat is automatically turned down at night. According to EU regulation new heat units have been required to be equipped with weather compensation since 2013/2015[5]. Since the majority of heat installations are already assumed to be equipped with heat uniform control systems and the remainder will follow in the years to come, this measure has not been examined further.

Multifunctional thermostatic circulation valves

For active energy efficiency measures within hot domestic water, multifunctional thermostatic circulation valves (MTCV) cases from Danfoss are suggesting energy savings of 25-36% in multi-family houses on energy used for hot domestic water (Danfoss, 2020). However, Danfoss uses a more conservative estimate of the potential for energy savings through MTCV for multi-story dwellings of 12% in a more recent assessment covering specifically the Danish building stock[6].

Danfoss Leanheat

An example of a model predictive control (MPC) system is the Danfoss product Leanheat, which provides a digital program that can control, provide information on, and co-manage the heating systems in large buildings. The system uses artificial intelligence to analyse temperature and humidity data from the apartments and on this basis it adjusts the flow temperature from the central heating system to the apartments. The model is dynamic and continuously collects the relevant information and dynamically adjusts the temperature level and the flow temperature according to the internal climate of the building and the current external weather conditions and weather forecasts.

Leanheat is particularly widespread in Finland, where it was originally developed, and has been integrated into the heating systems of many large housing companies. One of these housing companies is Espoon Asunnot,

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[5] https://ec.europa.eu/energy/sites/ener/files/documents/guidelinesspacewaterheaters_final.pdf

[6] Conversation with Danfoss, March 2021.

owning approximately 15,000 apartments in Espoo, Finland and now uses the technology in more than 5,000 of these apartments. In the first phase of the implementation of the system, the company was able to reduce heat consumption by almost 10%. In the second phase, the company focused on reducing peak consumption, and was able to do so by as much as 24% on average with the help of the system (Danfoss LEAN-heat, 2018).

Another example of the use of the Leanheat system is at the Finnish housing company Järvenpään Mestariasunnot, which owns about 2,000 apartments. The company has applied the system to a total of 1,370 apartments and has seen a reduction in heating needs of approx. 11% (Danfoss LEAN-heat, 2017). An added benefit of Leanheat is the possibility to use the control systems and the heat storage capacity of the building to adjust energy consumption to respond to price signals in energy markets. As the share of fluctuating energy sources like wind and solar power grows the economic and environmental benefit of providing flexibility will also increase.

3.2 Ventilation and cooling

In 2019, the identified electricity consumption for ventilation was 4.7 PJ and the energy consumption for cooling 3.4 PJ. The energy consumption is solely identified for the commercial and public services segments as the electricity use for ventilation and cooling is negligible in households.

Energy savings regarding ventilation are primarily savings on the space heating consumption of the building. However, it is also possible to achieve energy savings on the electricity used to drive the ventilation system through active measures.

For ventilation and cooling three layers have been identified:

- Timers (first layer)
- Demand control (second layer)
- Predictive control (all-layer)

Based on the current level of prevalence of the different layers and the potential overlap between measures, the overall (maximum, all-layer) identified saving potential withing electricity use for ventilation and cooling is:

Segment	**Saving potential** (Electricity) (Ventilation / Cooling)	**Energy use 2019 (PJ)** (Electricity) (Ventilation / Cooling)
Services		
- Private	11% / 20%	3.4 / 2.5
- Public	11% / 20%	1.3 / 0.9

The above potentials assume full utilization of all identified active energy efficiency measures within ventilation and cooling. Heat lost savings are included in the potential for space heating.

For prevalence of technologies today, see section 3.5.

Ventilation

Demand control of ventilation can help reduce the building's energy consumption by avoiding unnecessary ventilation. The control must ensure an energy-saving ventilation level that at the same time maintains a healthy indoor climate and allows the rate of ventilation to be adapted to the use of the building. The control can be based on the CO_2-levels, which are measured by room sensors and electronic control units, or which are manually regulated by the occupants of a dwelling, for instance. This type of on-demand control is also referred to as demand-controlled ventilation (DCV).

Examples of typical control methods/parameters:

- Timers
- Indoor temperature
- Moisture sensors (DCV-RH)
- Carbon level sensors (DCV-CO2)
- Presence/motion sensors (PIR) (DCV-IR)

Common sources of pollution to the indoor climate can generally be divided into:

- Building conditions (degassing from construction products and furniture, construction moisture, penetration of radon and earth gases)
- Volatile Organic Compounds, VOCs
- Human presence (bioeffluents, CO_2, moisture)
- Activities (e.g. bathing, cooking, laundry and drying)

The source of pollution and the type/use of the building influence which control method or combination of control methods is satisfactory. If ventilation is controlled solely according to the CO_2 content of the indoor air, when (too) few people stay in the room, it can lead to too low rates of air change in relation to the level of other contaminants and gases in the indoor climate. CO_2 sensors are therefore not sufficient on their own in e.g. housing, especially single-family houses, which are most often used by a few people on larger areas, but they can be used as an indicator of when people are present, which then triggers a basic ventilation. The same effect can be achieved by motion sensors (PIR), where it is also possible to record the number of people in the room. PIR sensors are suitable for use in needs-driven ventilation (SBi, 2012) .

For households, it is especially important that the control is not complex, expensive or that residents are deprived of the opportunity to manually influence the system.

In buildings with typically unevenly loaded rooms, such as schools and institutions or meeting rooms and canteens, relevant needs-driven ventilation can be organized from simple clock control/timers to more advanced sensor controls. For the ventilation to be adapted to current needs and the greatest possible energy savings, it is necessary to control each room in the building, which for large central installations can mean relatively complex and costly systems. Decentralised ventilation units in each room are an alternative that can limit construction costs and complexity (SBi, 2012) .

Cases - Ventilation

A recent case study of DCV in office and school buildings (Bart Merema, 2018) measured significant energy savings from both fans (50-55%) and ventilation heat losses (34-47%).

A Norwegian study (Mysen M, 2005) of various ventilation strategies in 157 classrooms at 81 schools in Oslo found that DCV-CO_2 and DCV-IR reduce energy consumption for ventilation in the average classroom to 38% and 51% respectively, compared to a CAV system that works with constant air volume from 07:00 to 17:00, respectively. A Swedish study (Pavlovas, 2004) of four ventilation strategies (CAV, DCV-CO_2, DCV-IR and DCV-RH) in connection to renovation of multi-storey housing, finds an energy saving potential of more than 50% for DCV-RH and DCV-CO2 and about 20% for DCV-IR compared to a CAV system. By a combination of DCR-RH and -CO2, (Nielsen, 2010) finds a savings potential of 35% in single-family homes. For larger and more complex DCV systems in large commercial buildings, the savings potential is 20%. (Menassa CC, 2013)

Cooling

Just like ventilation, demand control of cooling aims to ensure a good indoor climate and comfort level, which is adapted to the needs of the building occupants.

Mechanical cooling systems/compressors have been the most traditional way of creating cooling. It is a flexible, but also very energy-intensive way of cooling a building, where cold water is produced for cooling surfaces in an air handling unit or for cooling baffles directly in each room. A less energy-intensive alternative is free cooling, where either cold outdoor air, groundwater, lake water or seawater is used and where the energy is used for transport and heat exchange instead.

Factors that affect the need for cooling can generally be categorized as external, internal, and building-specific. Building-specific factors are usually static, where internal and external factors can vary greatly from time to time and day to day:

- Building-specific factors: e.g. the building's location and orientation.
- External factors: e.g. outdoor temperature, humidity, sunlight, wind direction and speed.
- Internal factors: indoor objects that generate or absorb sensitive or latent heat - mainly people, lighting and electrical appliances.

The occupancy rate (how many people use a room) is especially varying in commercial buildings, and a factor that affects the cooling need a lot. In addition to people generating heat and CO_2, the appliances that produce heat (radiators, lighting, fans, printers, etc.) are often also closely linked to human activity, just as the use of windows, doors and other openings in the building is. A study of the energy saving potential of demand-driven cooling in commercial buildings (individual and large-scale offices) found a saving of 20.3% compared to the base case (Adam Rysanek, 2017).

3.3 Electric lights

In 2019 the identified energy consumption for electric lights was 13.9 PJ corresponding to 21% of the overall electricity use within households and commercial and public services (excluding electricity used for heating purposes).

For electric lights two layers have been identified:

- Motion sensors (first layer)
- Daylight harvesting (all-layer)

Based on the current level of prevalence of the different layers and the potential overlap between measures, the overall (maximum, all-layer) identified saving potential withing electricity use lighting is:

Segment	Saving potential (Electricity)	Energy use 2019 (PJ) (Electricity)
Services		
- Private	30%	10.2
- Public	30%	3.7

The above potentials assume full utilization of all identified active energy efficiency measures within lighting.

For prevalence of technologies today, see section 3.5.

Active energy efficiency lighting measures cover various types of lighting control systems and the use of daylight inside the building (daylight harvesting). In addition to saving energy, the purpose of lighting control is also to ensure a good indoor climate and lighting environment. For a building's lighting system to be used optimally in terms of energy, the interaction between detection of presence (e.g., motion sensors) and the use of the room's natural light, is necessary.

Although many different lighting control systems are available, it is quite difficult to quantify their energy saving potential. The savings described below relate to the specific energy consumption for providing lighting and not to the overall energy demand of the building.

Motion sensors

Motion/presence sensors typically use passive infrared (PIR) or ultrasonic motion measurement technique. PIR sensors are the most widely used technology that works by detecting infrared radiation (radiant heat) in a room. The sensor can be adapted to the individual room and its typical users by adjusting the timing of when the light is turned off as the room is left, the sensitivity (how large objects it reacts to, e.g. dog, child, adult) and the light level (so that the light is not turned on when there is a lot of daylight supplementation). Sensor location and sensitivity must be sufficient as to not turn off general lighting in case of for instance sedentary work.

Intelligent light control also includes smart bulbs, where light is controlled with a remote control or smartphone. The control can be done according to scenarios where the lighting is adapted to the needs of the users, e.g. that the light is turned on slowly in the morning, or via GPS information about the location of the user, so that the light in a dwelling is automatically turned off when leaving home. Smart bulbs can also be connected to motion sensors.

Motion sensors have been used for many years in offices and have been shown to result in energy savings of between 20% and 60%. (Christel de Bakker, 2017) (Galasiu A. N., 2013) The technology is less common in homes, in addition to outdoor use by e.g. carport or as part of the home's anti-theft system (Viegand Maagøe, 2018).

Light control at the individual level

Light control systems are increasingly being developed to adapt lighting to individual needs, including using sensors with more defined control zones (granularity), so sensor detection, for example, takes place at desk level instead of room level. In two North American studies of the energy saving potential of desk-level sensors, relative savings were found at up to 40% compared to the base case, where the light was turned on and off manually during working hours (Galasiu A. N., 2013) (Rubinstein & Enscoe, 2010). A recent study finds an energy saving potential of 25-30% for individual motion sensors in offices (Christel de Bakker, 2017) .

Factors influencing the potential

The savings potential for lighting depends on light sources, habits, and consumption patterns. For example, there may be greater savings potential in lighting control in common rooms, as fewer people tend to turn off the light after themselves when they leave a common area – people do not feel that it is their room and right to turn off the light after themselves. An older American study (2000) of light control across different room "types" found that movement sensors in toilets had the greatest energy saving compared to baseline (47-60%) followed by classrooms (52-58%), conference rooms (39-50%), and personal offices (28-38%). The span depended on the timeout setting (how long it takes for the light to turn off when the room is left) — shorter timeouts equal greater savings. In multi-storey dwellings, light control of common areas is most often used for stairwells, cellars and ceilings.

The savings potential may also depend on whether those working in the same room have similar or diverse job functions. (Duarte, Van DenWymelenberg, & Rieger, 2013) (Pierrick Bouffaron, 2014). People with the same job function typically have similar ways of working (e.g. presence, time at the desk, walking to and from the work room, etc.), which is why the energy saving potential of e.g. individual lighting control does not result in significantly higher energy savings compared to room-level control. Light control at the individual level is associated with higher installation costs than at space level, and it may therefore be appropriate to consider the composition of work functions, if the energy savings of individual lighting control are to outweigh installation costs.

In addition to habits and consumption patterns, the light source and the amount of light generated also have an impact on energy saving potential. Two studies of the savings potential of (i) motion sensors alone, (ii)individual light control and (iii)the combination of the two, found a saving potential of 37% for individual lighting control of luminaires with high illumination strength (1000 lux) and 10-20% for luminaires with lower lighting strength (400 lux) (Galasiu A. N., 2009) (Galasiu A. N., 2007). According to Building Regulations (BR18) and relevant standards (DS/EN 12464-1 and DS/EN 12464-1 DK NA), the requirement for lighting strength today stands at 500 lux at the task area of an office and 300 lux for the general lighting strength in the rest of the room (typically ceiling-mounted lighting systems).

Daylight Harvesting

Access to daylight can have a major impact on people's well-being and can help reduce the energy consumption of buildings by means of lighting control systems. In Daylight Harvesting, daylight is used to offset the amount of electrical lighting needed for proper lighting of a room by dimming or changing electrical lighting in response to changes in daylight intake. The adjustment can be done via both exterior and interior window guards, which must at the same time alleviate overheating or nuisance created by direct sunlight.

Proper regulation of daylight incursions can significantly reduce annual energy consumption. However, the potential depends on many factors, which makes it difficult to quantify the potential for savings, such as the country's climate conditions, the north-south direction of the building and its surroundings, i.e. shade from trees or reflections from neighbouring buildings. Also, the building construction has influence, such as the shape of the building, the shape of the room - mostly the depth, interior light reflection and the size of windows and doors. The type and location of the electric lighting and the lighting control system used also have an impact on the potential. As a result of the difference between the many factors from study to study, very different energy saving potentials are reported for Daylight Harvesting.

According to the literature, the potential for savings for daylight harvesting can be as high as 60%. Two different research projects by the same author on daylight management in office buildings (D. H. Li, 2014) found energy savings of 33% and 50% respectively. Aghemo et al. measured potential (C. Aghemo, 2014) energy savings from 17% to 32% in offices, where Haq et al. sums up a saving potential of 20% to 31% in office buildings worldwide (M. A. u. Haq, 2014). Hackel and Schuetter (Schuetter, 2013) found an average energy saving potential of 63% in 20 office buildings in the United States. Yun et al. found (G. Y. Yun, 2012) a potential of up to 43% in a study of four offices over five months using automatic damping control. From a meta-analysis Williams et al. (A. Williams, 2012) concluded an average savings potential of 39% from daylight management in 73 office and school buildings, as a result of both measurements and simulations. Jennings et al. (J. Jennings, 2000) find a savings potential of 21% over a seven-month monitoring period with automatic daylight attenuation control.

3.4 Central control systems and digital solutions

The individual active energy efficiency measures for heating, ventilation, cooling and lighting can be combined and controlled through digital solutions that can ensure optimal energy savings and high level of comfort through coordinated control of the devices. These digital solutions should therefore be seen as an extra layer on top of the individual measures that can make them interact to ensure full exploitation of the potentials. Especially in larger buildings, the advantages of the central control systems are to avoid incorrect settings that result in waste of energy. Moreover, digital control of the overall system should lead to increased comfort while overviewing the condition of the building and installations can help ensure higher reliability and lower maintenance costs.

CBT/BMS/IBI

These central control systems for the energy consumption of buildings are known by different terms depending on the type of use. Central Condition Control Systems (CTS) typically cover systems in larger buildings that control and monitor the technical installations for heating, ventilation, and cooling. In addition to controlling these systems, the more advanced Building Management Systems (BMS) include integration with control of the building's other energy consumption, such as lights or alarms. Intelligent Building Installations (IBI) can be set to interact with BMS and CTS systems, and can provide intelligent and active control of components individually and in interaction with each other.

The EN 15232: 2012 Standard[7] for use in conjunction with the Energy Performance of Buildings Directive (EPBD) presents two different procedures for determining the impact of building automation and control systems functions on the energy efficiency of a building, one through an estimation based on available coefficients and another which require more detailed information on the building and the proposed changes. The standard coefficients show that moving a building from the reference class (C) building management system to a high efficiency system with individual room/zone control with communication between controllers and lock/blocking between heating and cooling control units would result in heat savings in order of 20-32% for buildings in the service sector (Schneider Electric).

According to a recent study by Waide Strategic Efficiency Limited (Waide, 2019) it would save 14% of total building primary energy consumption by 2038 if all measures within building automation and control systems set out in the EU's Energy Performance of Buildings Directive (EPBD), were properly implemented. Though these figures cannot be transferred directly to the Danish building stock, which is likely to be in a better condition, it indicates that the potential from active energy efficiency measures is considerable.

A concrete example of the use of BMS to reduce energy consumption and reduce the cost of operating and maintaining buildings comes from Schneider Electric, who has installed a BMS with the financial company Société Générale in France in a large campus complex and large office spaces. In addition to significant savings in maintenance and repair achieved through more detailed information on the condition of building elements, significant energy savings were achieved through the establishment of the system. All in all, an overall reduction of the buildings' energy consumption of 20% was achieved (Schneider Electric, 2019).

3.5 Overview of analysed measures

The identified potentials for active energy efficiency measures in the four building segments are summarized in Table 2. As can be seen from the literature review and the cases presented, the potentials vary greatly from building to building and the potentials presented below are therefore also subject to considerable uncertainty.

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[7] EN 15232:2012 Standard: Energy Performance of Buildings – Impact of Building Automation, Controls, and Building Management"

	Space heating		Lighting		Ventilation		Cooling		Domestic hot water	
Single-family	None	0%								
	Mechanical thermostats	7%								
		0%								
	Electronic thermostats	15%								
Multi-family	None	0%							None	0%
	Mechanical thermostats	7%								0%
	+ Dynamic balancing	15%								0%
	+ MPC	22%							MTCV	10%
Private	None	0%	None	0%	None	0%	None	0%	None	0%
	Mechanical thermostats	7%	Motion sensors	20%	Timers	15%	Timers	7%		0%
	+ Dynamic balancing	15%			+ Demand control	23%	+ Demand control	15%		0%
	+ MPC	29%	+ Daylight harvesting	36%	+ Predictive control	26%	+ Predictive control	29%	MTCV	10%
Public	None	0%	None	0%	None	0%	None	0%	None	0%
	Mechanical thermostats	4%	Motion sensors	20%	Timers	15%	Timers	7%		0%
	+ Dynamic balancing	15%			+ Demand control	23%	+ Demand control	15%		0%
	+ MPC	29%	+ Daylight harvesting	36%	+ Predictive control	26%	+ Predictive control	29%	MTCV	10%

Table 2: Saving potential in percentage for active energy efficiency measures. MTCV: Multifunctional thermostatic circulation valve.

In order to determine the potential that has not yet been fulfilled, the level of prevalence of the different technology-layers today are used. The level of prevalence is based on (Viegand Maagøe, 2018) and calibrated according to findings in the literature.

	Space heating		Lighting		Ventilation		Cooling		Domestic hot water	
Single-family	None	3%								
	Mechanical thermostats	91%								
		0%								
	Electronic thermostats	6%								
Multi-family	None	3%							None	100%
	Mechanical thermostats	91%								0%
	+ Dynamic balancing	3%								0%
	+ MPC	3%							MTCV	0%
Private	None	0%	None	70%	None	25%	None	25%	None	100%
	Mechanical thermostats	50%	Motion sensors	30%	Timers	25%	Timers	25%		0%
	+ Dynamic balancing	25%			+ Demand control	50%	+ Demand control	50%		0%
	+ MPC	25%	+ Daylight harvesting	0%	+ Predictive control	0%	+ Predictive control	0%	MTCV	0%
Public	None	0%	None	70%	None	25%	None	25%	None	100%
	Mechanical thermostats	50%	Motion sensors	30%	Timers	25%	Timers	25%		0%
	+ Dynamic balancing	25%			+ Demand control	50%	+ Demand control	50%		0%
	+ MPC	25%	+ Daylight harvesting	0%	+ Predictive control	0%	+ Predictive control	0%	MTCV	0%

Table 3: Level of prevalence today.

From the maximum saving potentials identified in Table 2 and the level of prevalence today in Table 3, the resulting saving potentials are calculated and shown in the table below:

Potentials 2019		Space heating	Lighting	Ventilation	Cooling	Domestic hot water
Households	Single-family	8%	0%	0%	0%	0%
	Multi-family	9%	0%	0%	0%	10%
Services	Private	15%	30%	11%	20%	10%
	Public	15%	30%	11%	20%	10%

Table 4: Resulting potentials in 2019.

The absolute saving potential for active energy efficiency measures is 22.9 PJ, of which 17.5 is heat and 4.9 electricity. Figure 5 below show the full identified potential divided between households and commercial and public services.

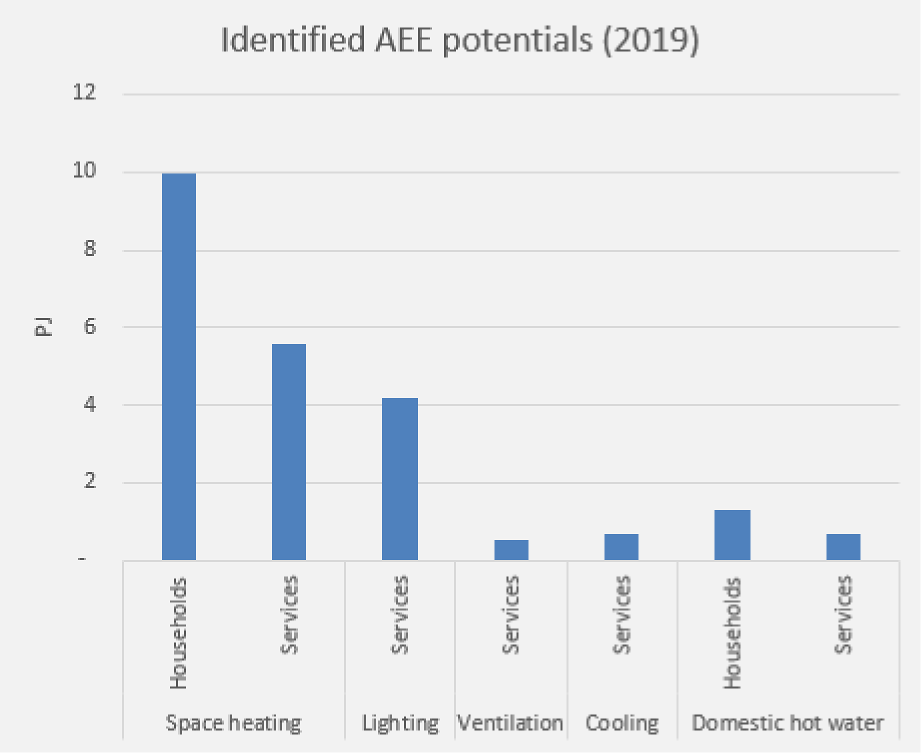


Figure 5: Absolute Identified saving potential for active energy efficiency (AEE) measures with the year 2019 as reference.

3.6 Systemic gains and multiple benefits

Possibility for reducing flow temperatures in district heating systems

As the heat-saving measures are spread and used in an increasing part of the building stock, it could also have an effect on the district heating systems, which deliver a large part of the heat to the Danish households and buildings.

With more efficient control of heat requirements and less energy loss, it will be possible to reduce the flow temperature in the district heating system to a greater extent. However, the flow temperature will to some extent be tied up to being able to provide sufficient heat performance for the less efficient part of the building segment, and it is therefore not realistic that the deployment of smarter and more efficient solutions will have a major impact on the district heating network right away. Over time, however, lower energy consumption in buildings will lead to decreasing requirements for the temperatures in the district heating network, and thus systemic gains can also be made by increasing the energy efficiency of the buildings. The benefits may be enlarged by focusing energy efficiency on the less efficient part of the building segment and buildings remotely located in district heating grids.

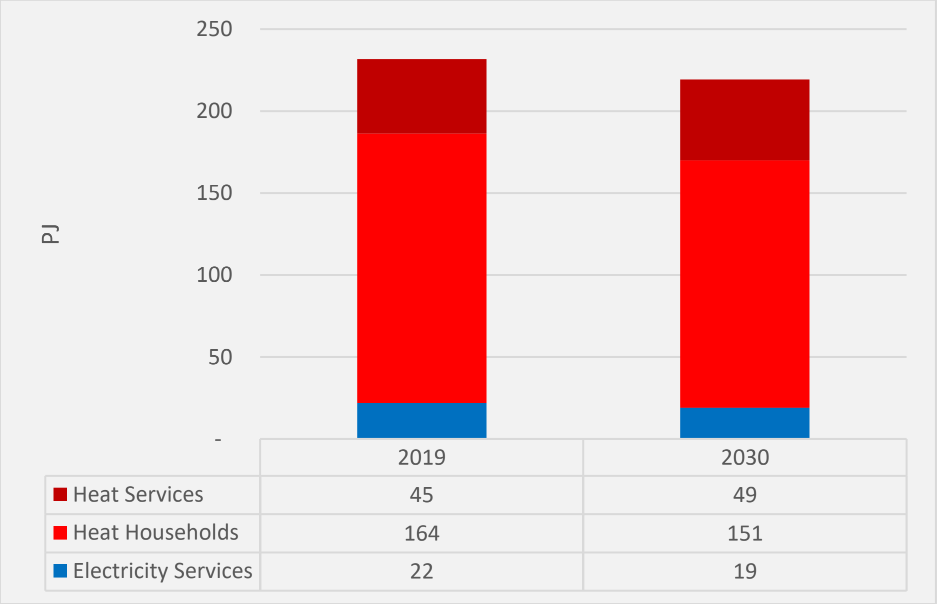
As already demonstrated by Leanheat, active solutions and digitalization, also enable buildings to interact with wider energy system allowing them to provide demand response to energy systems. Utilization the potential for demand response may provide economic benefits because the need for production on expensive peak load units can be reduced and at the same time demand response can contribute to integrating fluctuating renewable energy sources in both district heating systems and electrical systems.

Monitoring and measuring of the surrounding conditions are key to most active energy efficiency technologies. In addition to delivering energy savings the increased digitalisation and automatization may hold multiple benefits for building owners and users, for example through monitoring the moisture and CO_2-content of the air in apartments or by improving indoor air quality by ensuring adequate ventilation. As described in the paper “Economic Assessment of multiple benefit” (Værdisætning af multiple benefits) (Energianalyse, 2020) the potential benefits for the society from reducing indoor pollution and mould are significant.

4 Active energy efficiency potential towards 2030

Denmark's Energy and Climate Outlook 2021 (DECO21) has been used to project the energy consumption for heat and electricity in the analysed scope in 2030. The energy consumption has been distributed to end use categories (i.e., space heating, domestic water, lighting, ventilation, cooling) from the distribution factors in 2019, as seen in Appendix A. The projection includes 8 PJ heat from surroundings (used by heat pumps) in 2019 increasing to 24 PJ in 2030.

Towards 2030, the energy consumption for space heating and domestic water decreases by 8% for households and increases by 9% for commercial and public services. It is assumed that electricity used for lighting decreases 2.5% annually because LED lights are phased in. The overall analysed electricity consumption decreases by 16% between 2019 and 2030.



	2019	2030
🟥 Heat Services	45	49
🟥 Heat Households	164	151
🟦 Electricity Services	22	19

Figure 6: Development for the energy consumption towards 2030 for the analysed scope. Based on DECO21.

The development in level of prevalence of technologies in 2030 is based on (Viegand Maagøe, 2018) and calibrated according to findings in literature. These levels have been used to make an updated potential for active energy efficiency measures, seen in Figure 7. The updated potentials are based on the projected energy consumption in 2030.

	Space heating		Lighting		Ventilation		Cooling		Domestic hot water	
Single-family	None	0%								
	Mechanical thermostats	70%								
		0%								
	Electronic thermostats	30%								
Multi-family	None	0%							None	95%
	Mechanical thermostats	65%								0%
	+ Dynamic balancing	30%								0%
	+ MPC	5%							MTCV	5%
Private	None	0%	None	30%	None	25%	None	0%	None	95%
	Mechanical thermostats	50%	Motion sensors	60%	Timers	25%	Timers	60%		0%
	+ Dynamic balancing	20%			+ Demand control	50%	+ Demand control	35%		0%
	+ MPC	30%	+ Daylight harvesting	10%	+ Predictive control	0%	+ Predictive control	5%	MTCV	5%
Public	None	0%	None	30%	None	25%	None	0%	None	95%
	Mechanical thermostats	50%	Motion sensors	60%	Timers	25%	Timers	60%		0%
	+ Dynamic balancing	20%			+ Demand control	50%	+ Demand control	35%		0%
	+ MPC	30%	+ Daylight harvesting	10%	+ Predictive control	0%	+ Predictive control	5%	MTCV	5%

Table 5: Level of prevalence 2030.

Potentials 2030		Space heating	Lighting	Ventilation	Cooling	Domestic hot water
Households	Single-family	6%	0%	0%	0%	0%
	Multi-family	7%	0%	0%	0%	10%
Services	Private	14%	20%	8%	18%	10%
	Public	14%	20%	8%	18%	10%

Table 6: Resulting potentials in 2030.

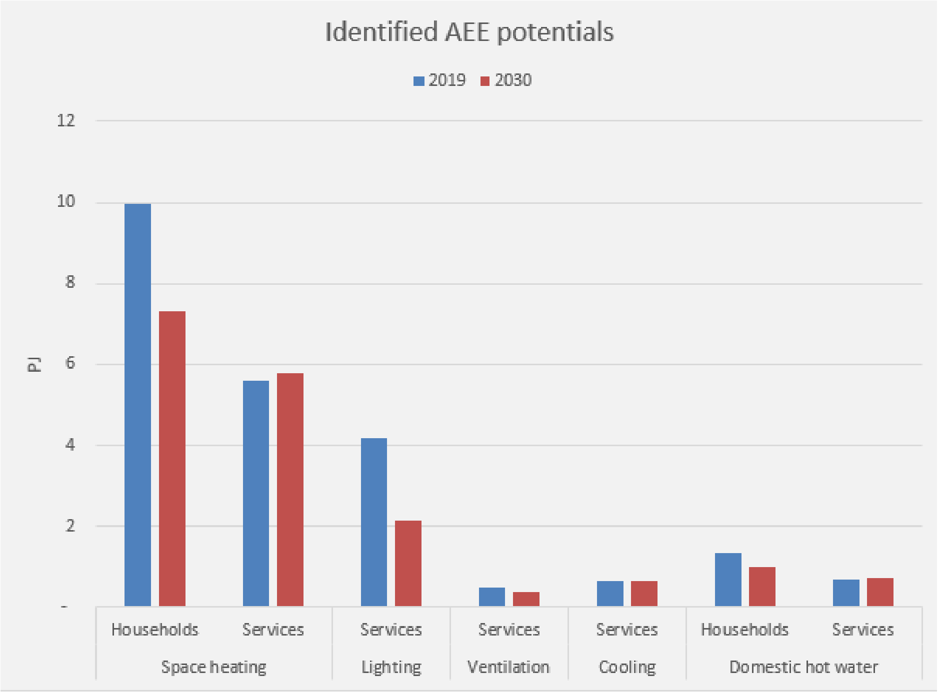


Figure 7: Identified potentials calculated from level of prevalence in 2030 and the projected energy consumption in 2030.

The difference between the potentials in 2019 and the potentials in 2030 based on the projected energy consumption is assumed to come from natural development and measures in the already stated policies and effects of the energy agreements of June 2020. The difference corresponds to 4.9 PJ.

The non-achieved potential for further active energy efficiency measures is therefore identified to be 18.0 PJ towards 2030, seen on the figure below as the difference between the blue line and red line.

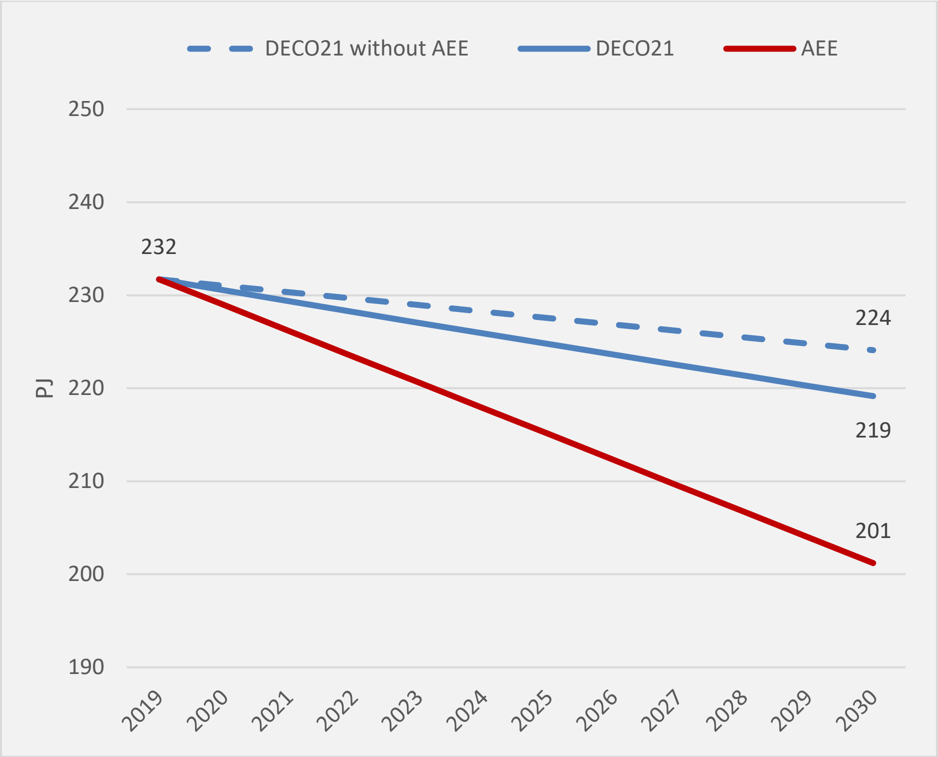


Figure 8: Projection for energy consumption in analysed scope towards 2030 (including surrounding heat from heat pumps).

4.1 Socio-economic potential

The socio-economically viable level of energy savings is determined by comparing the costs of implementing energy savings with the marginal socio-economic costs of energy supply. The analysis focuses strictly on technology related costs, which means that costs related to policy measures (administrative costs, tax distortion effects etc.) have not been quantified.

Implementing the full potential for active energy efficiency measures is estimated to yield a socio-economic benefit of approx. 590 mill. DKK/annually by 2030. The greatest potential lies within space heating and domestic hot water, which also represent the largest energy demands.

The benefits of energy savings mainly consist of a reduced need for production of energy and savings in energy infrastructure. It is assumed that the heat supply in 2030 is based on green energy technologies, in the form of district heating and heat pumps.

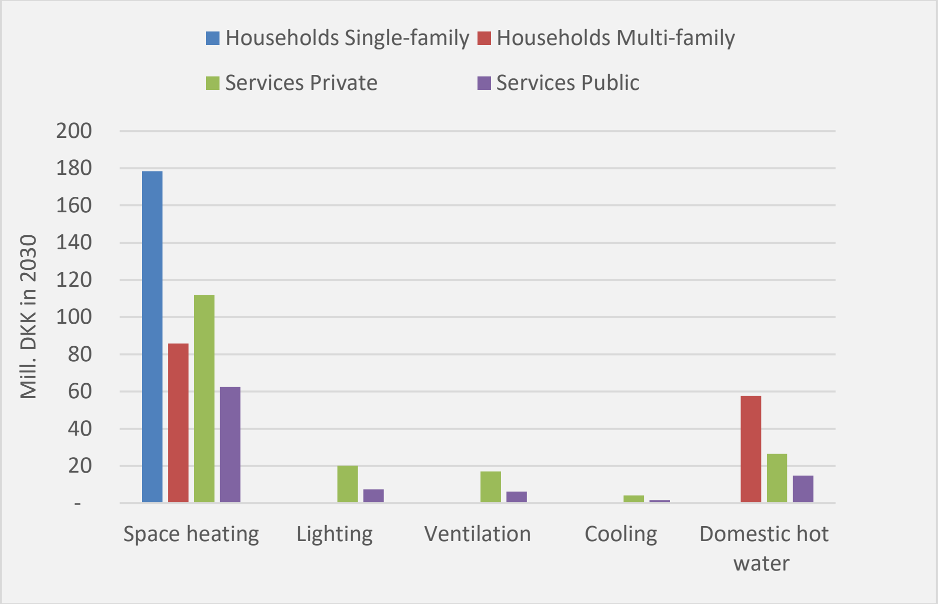


Figure 9: Economic benefit for the society by 2030 from implementing active energy efficiency measures distributed on end-uses and sectors.

4.2 CO_2-reductions

Assuming that it is possible to gradually implement the total active energy efficiency potential between 2022 and 2030, a greenhouse gas reduction of approximately 1.2 Mt CO_2 can be obtained over the same period. The CO_2 emissions reductions achieved by the end of the period are modest because electricity and district heating supply are assumed to be based almost entirely on renewable energy by 2030.

4.3 Assumptions underlying the economic assessment

The cost of implementing active energy efficiency measures within heating and domestic hot water are based on experiences from Danfoss. For the other energy service (lighting, cooling and ventilation) the cost figures based on Viegand and Maagøe (Viegand Maagøe, 2018), who has relied on a US report "Smart Buildings: Using Smart Technology to Save Energy in Existing Buildings" produced by the American Council for an Energy-Efficient Economy. The cost of light-savings has been adjusted to consider that LED is becoming the favoured choice of lighting in most buildings.

Investment (DKK/kWh)	Space heating	Lighting	Ventilation	Cooling	Domestic hot water
Single-family	2.6				
Multi-family	2.1				0.9
Private	2.0	6.6	3.3	4.9	0.9
Public	2.0	6.6	3.3	4.9	0.9

Table 7: Investment cost of energy saving measures used for the economic assessments.

The following assumption on lifetimes of the various measures are applied.

Life-time of measures	Space heating	Lighting	Ventilation	Cooling	Domestic hot water
Single-family	15				
Multi-family	15				15
Private	15	15	10	10	15
Public	15	15	10	10	15

Table 8: Assumed technical lifetimes of active energy measures.

A socio-economic discount rate of 3.5% is used.

Cost of energy

To determine the socio-economically optimal level of energy savings, the cost of saving energy must be weighed against the marginal socio-economic costs of supplying energy. The analysis of the marginal supply costs is based on own calculations. In 2030, the energy system is assumed to be well under way in the green transition, and therefore only district heating solutions and electric heat pumps arerelevant heat supply options. The marginal heat supply costs are calculated for two building types: single-family houses and larger buildings. Single-family houses represent detached houses and terraced houses, while larger buildings represent private and public multi-storey dwellings, public buildings and commercial buildings.

The marginal supply costs associated with heating the existing building stock reflect the cost savings that will be achieved when energy efficiency measures are implemented in the buildings. A system perspective has been applied, stretching from energy production, over infrastructure and to heat and electricity consumers. Because we take a socio-economic approach, energy taxes and duties are disregarded. For all technologies, the largest single saving lies in the purchase of energy in the form of electricity and district heating, but other synergies are considered as well. Heat savings allow building owners to invest in a slightly smaller and thus slightly cheaper heat pump, and a higher efficiency may be achieved in the heat unit because the flow temperature in the heating system can be lowered. Similar gains can be achieved in the district heating network, which is equipped with heat pumps. The report “Socio-economic value of heat savings” (Ea Energianalyse, 2017) provides a more detailed review of the methodological approach to calculating supply costs.

The marginal cost of electricity is estimated at 620 DKK/MWh (whole-sale electricity price of 360 DKK/MWh, 100 DKK/MWh for transmission and 160 DKK/MWh for distribution.

The marginal cost of district heating is 81 DKK/GJ for small buildings and 80 DKK/GJ for large buildings. The district heating solution is assumed to rely on a heat pump with a gas boiler as back-up.

The marginal cost of the individual heat pumps is 110 DKK/ GJ in small-buildings and 81 DKK/GJ in large buildings.

5 References

A. Williams, B. A. (2012). *Lighting Controls in Commercial Buildings.* LEUKOS, The Journal of the Illuminating Engineering Society of North America, vol. 8, no. 3, pp. 161-180.

Adam Rysanek, Y. P. (2017). *Occupancy learning-based demand-driven cooling control for office spaces.* Building and Environment 122.

Bart Merema, M. D. (2018). *Demand controlled ventilation (DCV) in school and office buildings: Lessons learnt from case studies.* Energy and Buildins 172, p. 349-360.

Bolius. (2018). *Bolius Boligejeranalyse.*

C. Aghemo, L. B. (2014). *Building automation and control systems: A case study to evaluate the energy and environmental performances of a lighting control system in offices.* Automation in Construction, vol. 43, no. July, pp. 10-22.

Christel de Bakker, T. v. (2017). *The Energy Saving Potential of Occupancy-Based Lighting Control Strategies in Open-Plan Offices: The Influence of Occupancy Patterns.* Energies.

Chung, T., & Burnett, J. (2009). *On the Prediction of Lighting Energy Savings Achieved by Occupancy Sensors.* Energy Eng. 98, 6–23.

D. H. Li, A. C. (2014). *Study of daylight data and lighting energy savings for atrium corridors with lighting dimming controls.* Energy and Buildings, vol. 72, no. April, pp. 457-464.

Danfoss. (2014). *Comfort and control are easy to handle with Danfoss electronic thermostats.* Danfoss.

Danfoss. (2014, September). *danfoss.com*. Retrieved from https://assets.danfoss.com/documents/98727/AE141986407255en-010201.pdf

Danfoss. (2020). *Danfoss solution for effective prevention from Legionella bacteria in Hospitals and Hotels.*

Danfoss LEAN-heat. (2017, Juni 18). *Leanheat.com*. Retrieved from https://leanheat.com/2017/06/18/case-jarvenpaan-mestariasunnot/

Danfoss LEAN-heat. (2018, 5 02). *Leanheat.com*. Retrieved from https://leanheat.com/2018/02/05/case-espoon-asunnot/

Dansk Byggeri. (2019). *Byggeriets Energianalyse 2019.*

Dansk Fjernvarme. (2017). *Intelligente fjernvarmeinstallationer: Fjernvarmeunits og tekniske tiltag er under udvikling.*

DTU. (2016). *Indeklima i skoler.* Center for Indeklima og Energi ved Danmarks Tekniske Universitet.

Duarte, C., Van DenWymelenberg, K., & Rieger, C. (2013). *Revealing occupancy patterns in an office building through the use of occupancy sensor data.* . Energy Build, 67, 587–595. .

Ea Energianalyse. (2017). *Samfundsøkonomisk værdi af varmebesparelser (Socio-economic value of heat savings).*

Ea Energianalyse. (2018). *Det samfundsøkonomiske potentiale for energibesparelser.*

ECOFYS. (2016). *Energy & GHG Emission savings potentials of thermostatic valves.*

Energianalyse, E. (2020). *Economic assessment of multiple-benefits (Værdisætning af multiple benefits).*

G. Y. Yun, H. K. (2012). *Effects of occupancy and lighting use patterns on lighting energy consumption.* Energy and Buildings, vol. 46, no. March, pp. 152-158.

Galasiu, A. N. (2007). *Energy saving lighting control systems for open-plan offices: A field study.* Leukos, 4(1): 7-29. .

Galasiu, A. N. (2009). *Energy savings due to occupancy sensors and personal controls: A pilot field study.* National Research Council Canada.

Galasiu, A. N. (2013). *Energy Saving Lighting Control Systems for Open-Plan Offices: A Field Study.* LEUKOS, 4, 7–29.

Galasiu, A., Newsham, G., Suvagau, C., & Sander, D. (2013). *Energy Saving Lighting Control Systems for Open-Plan Offices: A Field Study.* LEUKOS, 4, 7–29.

Galasiu, M. R. (2003). *Energy performance of daylight-linked automatic lighting control systems in large atrium spaces: report on two field-monitored case studies.* Energy and Buildings, vol. 35, pp. 441-461.

Guzek, G. (2009). *Zur Energieeinsparung in Heizungsanlagen durch den hydraulischen Abgleich.*

Irrek, W. (2005). *Optimierung der Heizungssysteme und hocheffiziente Umwälzpumpen in grösseren Gebäuden.* Umwelt, Energie GmbH im Wissenschaftszentrum Nordrhein-Westfalen - Abschlussbericht.

J. Jennings, F. R. (2000). *Comparison of control options in private offices in an advanced lighting controls testbed.* Journal Of The Illuminating Engineering Society, vol. 29, pp. 39-60.

Kimmels, A. (2011). *Shower Heat Recovery - Overview of Commercially Available DWHR Systems.* Retrieved from https://docplayer.net/1826540-Shower-heat-recovery-overview-of-commercially-available-dwhr-systems.html

King, J. (2018). *Energy Impacts of Smart Home Technologies.* American Council for an Energy-Efficient Economy.

Knudsen, J. S. (2019). *Varmt brugsvand i parcelhuse.* Aalborg University, Indoor Environmental and Energy Engineering.

M. A. u. Haq, M. Y. (2014). *A review on lighting control technologies in commercial buildings, their performance and affecting factors.* Renewable and Sustainable Energy Reviews, vol. 33, pp. 268-279.

Marco Pritoni, A. K. (2015). *Energy efficiency and the misuse of programmable thermostats: The.* Elsevier, Energy Research & Social Science.

Menassa CC, T. N. (2013). *A framework for automated control and commissioning of hybrid ventilationsystems in complex buildings.* Autom Constr;30:94–103.

Mysen M, B. S. (2005). *Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools.* Energy Build.

Nielsen, T. R. (2010). *Energy efficient demand controlled ventilation in single family houses.* Energy and Buildings.

Osjnik, M., Kolb, S., Chambris, A., & Schramm, H. (2017). *Hydronic balancing and control - how to overcome the global challenge of reducing energy use in multifamily housing.*

Pavlovas, V. (2004). *Demand controlled ventilation: A case study for existing Swedish multifamily buildings.* Energy & Buildings.

Pierrick Bouffaron, T. P. (2014). *Occupancy Diversity Factors in Buildings Using Sensor Data.* Behavior, Energy and Climate Change Conference, Washington, DC, USA, 7–10 December.

Rosemann, C. d. (2017). *The Energy Saving Potential of Occupancy-Based Lighting Control Strategiesin Open-Plan Offices: The Influence of Occupancy Patterns.* Energies.

Rubinstein, F., & Enscoe, A. (2010). *Saving energy with highly-controlled lighting in an open-plan office.* . LEUKOS, 7, 21–36.

Sabina Kordana, K. P. (2019). *Opportunities and Threats of Implementing Drain.* MDPI, Resources 2019, 8, 88;.

SBi. (2009). *Varmt Brugsvand - Måling af forbrug og varmetab fra cirkulationsledninger, SBi 2009:10.* SBi.

SBi. (2012). *Vejledning om behovsstyret ventilation - Boliger, børneinstitutioner og skoler.* SBi.

Schneider Electric. (2019, September). *www.schneider-eletric.com*. Retrieved from https://download.schneider-electric.com/files?p_enDocType=Customer+success+story&p_File_Name=The-Dunes-success-story-998-20609695-September.2019.pdf&p_Doc_Ref=998-20609695

Schuetter, S. H. (2013). *Commissioning for optimal savings from daylight control.* Energy Center of Wisconsin, Minnesota Department of Commerce, Division of Energy Resources.

Schweikhardt, F. (2017). *Hydraulischer Abgleich und Heizungspumpentausch - Ein Pilotprojekt der Evangelischen Landeskirchen in Baden.*

Seifert, J., & Meinzenbach, A. K. (2014). *Energetischer Vergleich von thermostatischen Heizkörperventilen mit und ohne Durchflussregelung.*

Statistics Denmark BOL103. (2020, March 3). *Statistikbanken*. Retrieved from www.statistikbanken.dk.

Statistics Denmark BYGB12. (2020).

Statistics Denmark BYGB34. (2020).

Viegand Maagøe. (2018). *Gevinster ved øget brug af data og digitalisering i bygnignsdrift.*

Waide, P. (2019). *The impact of the revision of the EPBD on energy savings from the use of building automation and controls.* Waide Strategic Efficiency Limited 2019.

Appendix A: Distribution of final energy consumption in 2019

Distribution	Private	Public	Single-family	Multi-family
Heat (TJ)	29.118	16.233	114.001	42.486
Space heating	85%	85%	83%	69%
Domestic water	15%	15%	17%	31%
Electricity (TJ)	27.441	8.319	23.027	8.491
Lights	37%	45%	0%	0%
Cooling	9%	11%	0%	0%
Ventilation	13%	15%	0%	0%
Remaining electricity (outside scope)	*41%*	*29%*	*100%*	*100%*

Appendix B: The Danish building stock

The residential building stock

Danish housing conditions are characterized by a large share of single-family houses and a large proportion of homes built before 1980. As of 2020, there were approximately 2.85 million private homes in Denmark (Statistics Denmark BOL103, 2020). According to Statistics Denmark, the average number of people in a dwelling has been reduced from 2.7 in 1970 to 2.1 in 2020 (according to Eurostat, the average for Denmark was 2.0 and the EU28 average was 2.3 in 2018).

Age and type

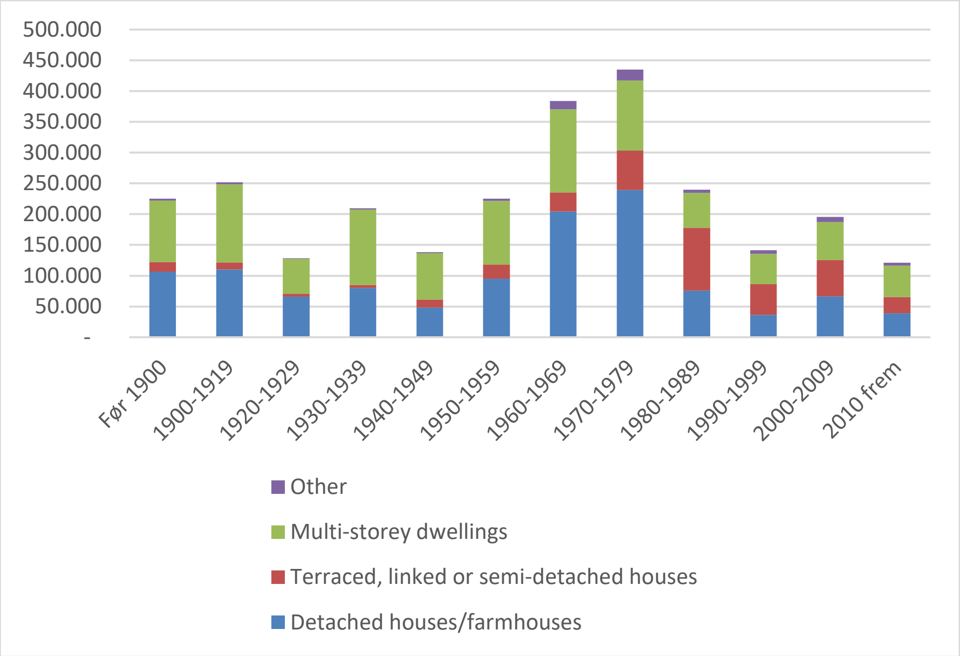


Figure 10: Number of Danish homes in 2020 by type and year of construction. The 'Other' category covers student housing/dormatories, residential buildings for communities (institutions) and holiday homes used as year-round housing. Only buildings heated for year-round use are shown. Source: Statistics Denmark, BOL102.

More than half of the current homes in Denmark were built before 1970, while approx. 74% were built before 1980. The Danish housing stock consists mainly of:

- **detached houses/farmhouses** (the majority built in the early 1900s and from the early 60s to the late 70s),
- **multi-storey dwellings** (from before the 20th century and up to the 80s) and
- **terraced, linked or semi-detached** houses (which are mainly built from the 60s and onwards).

- **Other** forms of housing in Denmark are dormitories, residential buildings for communities (institutions) and holiday homes used as year-round housing. The other forms of housing make up only about 2.5% of the total housing stock.

Building size

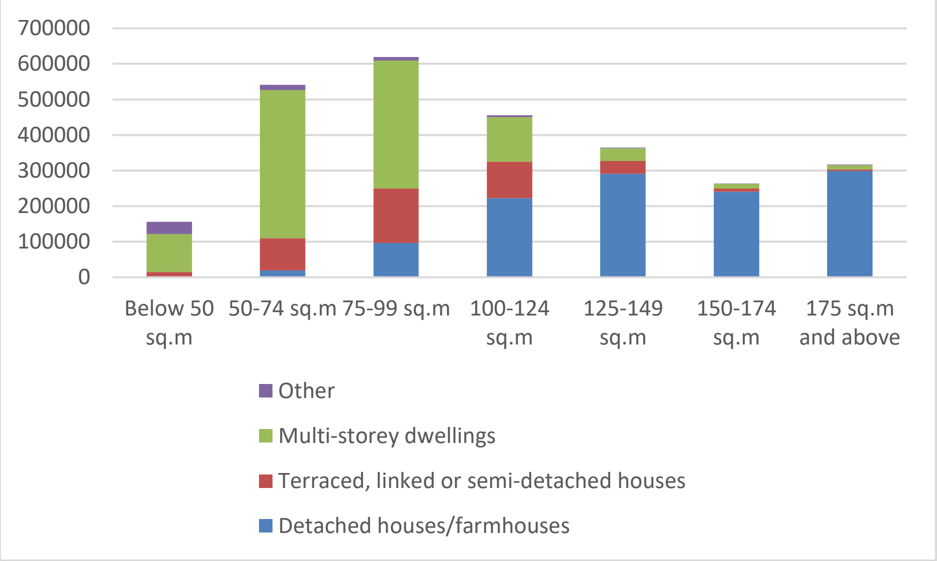


Figure 11: Number of Danish homes in 2020 by type and square meters (sq.m) of living area. Source: Statistics Denmark, 2020 (BOL103).

The largest share of Danish homes is between 75 and 99 m^2. Small homes of less than 74 m^2 consist mainly of multi-storey dwellings, while the majority of homes over 100 m^2 consist of detached houses/farmhouses.

Danish homes are increasing in size. According to Statistics Denmark, the average living space per person increased from 43 m^2 in 1980 to 52 m^2 in 2018. An important reason is that more people live alone. Another reason is that Danish homes are built larger than in the past. The average area per housing has increased from 106 m^2 in 1981 to 112 m^2 in 2018 (DST, 2019).

Energy performance of buildings

In 2018, almost 635,000 of the total 2,700,000 Danish homes were energy-labeled (an increase of 20% from 2016 (Dansk Byggeri, 2019). 51% of the energy-labelled homes have energy label C or D. 33% of the homes have energy label E or worse, while the remaining 16% have energy label A or B. The proportion of detached / farmhouses with energy label E or worse is significantly higher than is the case for terraced, chain and semi-detached houses and multi-storey dwellings.

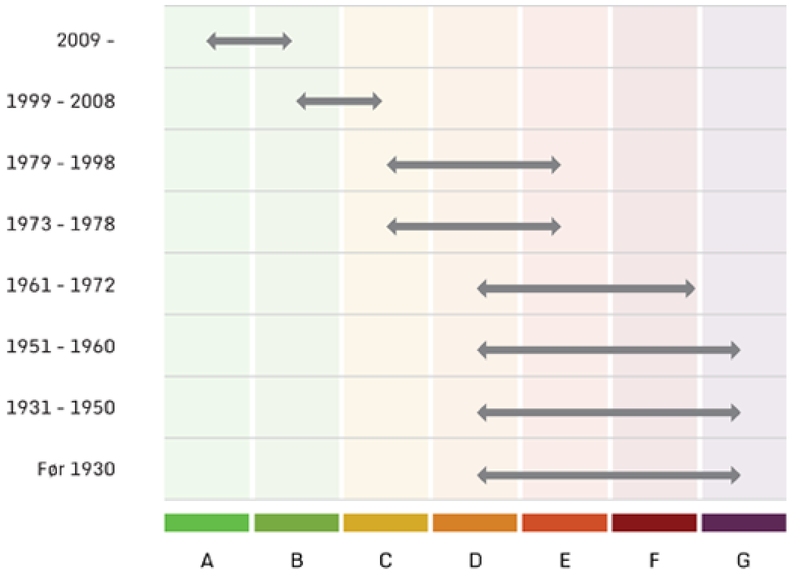


Figure 12: Statistical distribution of energy labels by year of construction. Figure from the Danish Energy Agency.

There is a connection between the year of construction and the home's energy label. The older the home, the poorer the energy label. The majority of detached / farmhouses were built before 1980, which explains the poor energy labelling of this segment.

Commercial and public buildings

The categories for commercial and public buildings consist of:

- Office, trade, inventory, incl. public administration
- Hotel, restaurant, hairdresser, and other services
- Library, church, museum etc
- Building for education and research (schools, laboratory etc.)
- Building for hospital, home, maternity home etc.
- Day-care institution
- Non-specified welfare institutions
- Sports centres, club houses

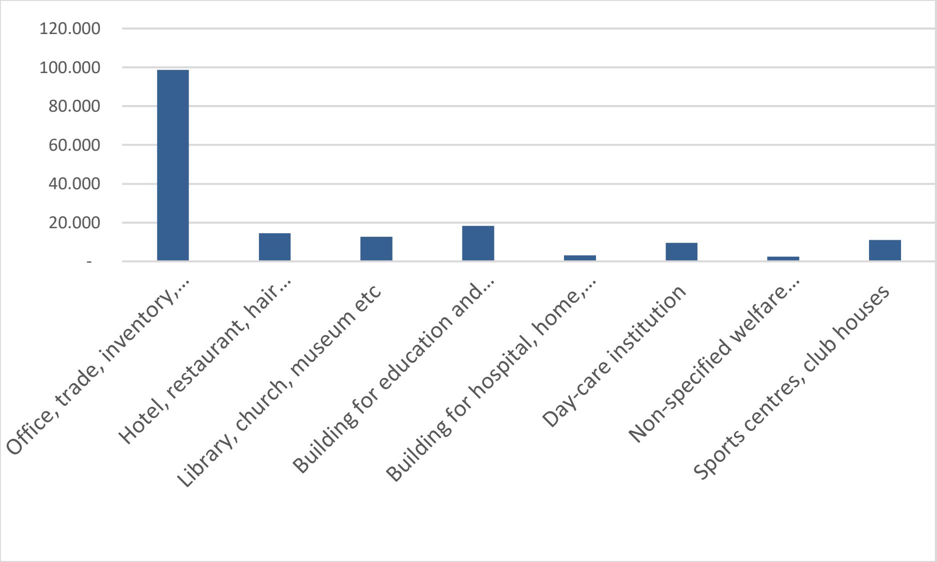


Figure 13: The number of Danish buildings used for businesses, offices, institutions, 2020. Source: Statistics Denmark (BYGB12).

Most of the buildings in this group lie within the category offices, trade, warehouses, administration, etc. For this category, the vast majority of the building stock has been built from the 1960s onwards (with especially many buildings built in recent times). In addition, a significant part of the building stock is from before 1900. Buildings used for education and research were mainly built from the 1950s to the 1980s. Thereafter, the construction of new buildings has fallen to a fixed low level.

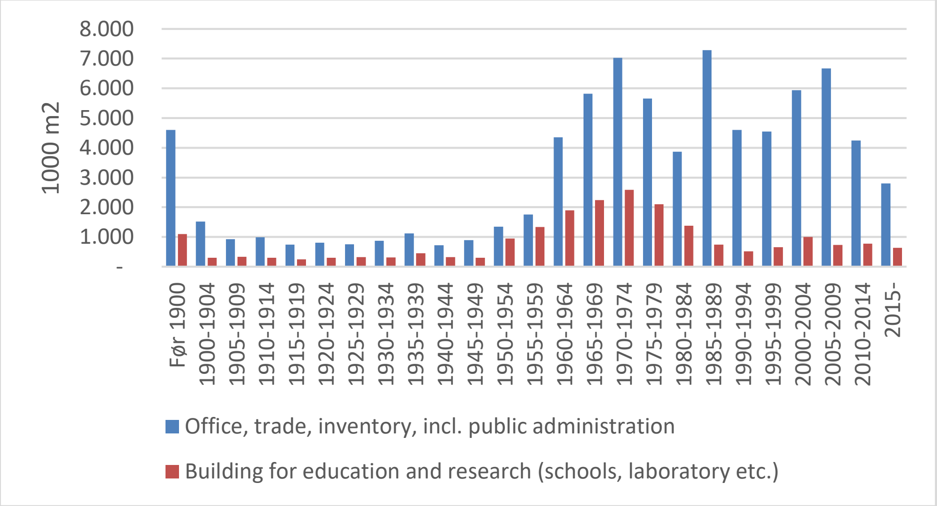


Figure 14: The area of the building stock for the two largest categories of buildings not used for housing as of 2020. Divided by year of construction. Source: Statistics Denmark (BYGB34).