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ORIGINAL ARTICLE

Cost-effectiveness of energy efficiency improvements for a residential building stock in a Danish district heating area

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Abstract The residential building stock holds a large energy efficiency improvement potential related to energy upgrading of the building envelope. Details about the heterogeneity of the building stock are paramount to perform a proper assessment of attractive energy efficiency improvements for end-users. Based on a sample of buildings, the study develops methods to identify potentials for heterogeneous building-tailored energy efficiency improvements, to reduce heat consumption, and evaluates their cost-effectiveness in the framework of a district heating area in Denmark. The study accounts for rebound effects and develops both technical (gross) and more realistic (net) potentials, allowing a more accurate analysis of attractive energy efficiency improvements. The analysis is novel as the underlying model relies on building characteristics rather than synthetic archetypes, which can lead to loss of diversity (e.g. in variation of costs and potentials) and thereby discarding cost-effective potentials. The analysis also investigates the sensitivity of the results to assumptions about the discount rate and focuses on the effect of exposing the end-user to different district heating tariffs and the consequent total cost-effective investments. The outcomes show that cost-effective energy efficiency improvements vary considerably, in size and type, among the heterogeneous building stock considered. In regard to district heating tariffs, when all the cost components are variable, the total cost-effective potential increases considerably, with specific energy efficiency improvements distributed differently among building categories, and with the cost components providing different incentives to invest. Heterogeneity, and different tariff policies, thus does matter, when evaluating economically attractive investments in energy efficiency improvements for buildings.

Keywords Cost-effective energy efficiency improvements · Heterogeneous building characteristics · District heating tariffs · Energy performance certificates · Rebound effects

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Introduction

In the framework of mapping paths towards a more sustainable future, energy efficiency and renewable energy-based technologies can provide cost-effective ways of decarbonising the European energy system (Baldini and Klinge Jacobsen 2016). From the energy demand perspective, buildings play an important role in the European strategy to reduce greenhouse gas emissions and limit the impact on climate change, as they account for approximately 40% of the total energy consumption in the EU (European Commission 2018).

The low energy efficiency of the (ageing) building stock makes buildings a target for energy upgrading, aiming at reducing their energy consumption (Lechtenböhmer and Schüring 2011; Zegarac Leskovar et al. 2019; Felius et al. 2020). To this end, European directives, for instance, the Energy Efficiency Directive (EED) (European Commision 2012) or the Energy Performance of Buildings Directive (EPBD) (European Commision 2010), have been set in place to regulate the renovation process, requiring member states to improve the energy efficiency of their building stocks as long as the investment is cost effective.

Worldwide case and review studies from the literature highlight the economic, energy and social benefits of building renovation, focusing on different aspects of the retrofitting process (Jensen et al. 2018; Amoruso et al. 2018). For instance, Santangelo et al. (2018) study renovation strategies for the Italian public housing stock, applying building energy simulation and occupant behaviour modelling to support the decision-making process, while Abdul Hamid et al. (2018) propose a review on the choices of different renovation strategies as well as decisions on renovation measures. In a different context, Krarti and Dubey (2018) investigate the outcomes of a potential energy retrofit programme, assessing the economic and environmental benefits of improving energy efficiency for the existing UAE building stock, while Ekström et al. (2018) evaluate the cost-effectiveness of renovating single-family houses to Passive House level, as compared to maintaining the existing buildings or renovating according to building regulation levels. Ballarini et al. (2017) focus instead on the energy and cost analysis through the application of the building typology, when investigating energy refurbishment of the Italian residential building stock. Last, despite a larger focus on the technical outcomes of the building renovation (Lešnik et al. 2018; Zegarac Leskovar et al. 2019), other studies point to the need for retrofitting buildings to improve the quality of life and social sustainability, for instance, by improving indoor climate conditions (Jensen et al. 2018; Sarran et al. 2020; Felius et al. 2020).

In the residential sector, the consumer can decide to invest in energy efficiency improvements such as more energy-efficient windows or insulation of walls, floors and ceilings in order to improve the energy performance of the building. From an economic perspective, the attractiveness of saving options for the private end-user can be evaluated by comparing investment costs and resulting heat savings with the cost of the heat supply replaced (Burgett et al. 2013; Mata et al. 2015). The cost-effectiveness is thus directly linked with the heat source, being, e.g. an individual boiler powered by natural gas, heat from district heating network or heat pumps. Furthermore, due to the large heterogeneity of the building stock, the attractiveness can also depend on tailored building-physical characteristics, being, for instance, the material of the existing element suitable for replacement (e.g. concrete, bricks, insulation material), the year of construction or the location of the building (e.g. facade facing north/south). Other elements, such as the building energy performance certificate or rebound effects, should be also accounted for.

Although a heterogeneous approach is often preferred when assessing building energy efficiency improvements, the literature shows that it is challenging to develop tailored data for large existing building stocks and validate them against real measurements (Brøgger and Wittchen 2018). Bottom-up building physics-based models are mostly used for this purpose, as they allow to assess the potential for energy efficiency improvements, given an energy upgrade of building components, e.g. roofs or external walls (Kragh and Wittchen 2014; Ó Broin et al. 2015). These models are often referred to as engineering methods (Swan and Ugursal 2009) or first-principle methods, being mostly based on a description of the thermal characteristics of the considered building stock. Models of this type often use building archetypes (i.e. synthetic/average buildings), for assessing the potential for energy efficiency improvements (Wittchen et al. 2017; TABULA Project Team 2012). Although straightforward, the use of archetypes is associated with loss of diversity, i.e. archetype heterogeneity (Booth et al. 2012), which could have an impact on the cost-effectiveness of an energy efficiency improvement, e.g. if the actual energy performance of a particular building was different from the archetype. Hybrid models represent a potential solution to overcome the drawbacks of traditional building physics (engineering)–based modelling methods. For instance, the hybrid modelling method proposed by Brøgger et al. (2019) allows to improve estimates on the average potential for energy efficiency improvements of building stock, considering, e.g. accurate prediction of the energy use in buildings, as well as estimating effects of imposing energy efficiency improvements.

On the basis of these considerations, we employ the method illustrated by Brøgger et al. (2018) to develop gross (technical) heat-saving potentials anew for an extensive number of energy efficiency improvements (e.g. windows, external walls, roofs, etc.), based on the characteristics of existing Danish buildings at the individual component level (e.g. area, orientation of the house, component materials or thickness). To account for possible overestimation of heat-saving potentials in buildings, because of implicit factors such as rebound and pre-bound behaviour by the inhabitants or building thermal characteristics after an energy upgrade (Haas et al. 1998; Hens et al. 2010), the analysis also estimates net (realistic) heat-saving potentials (i.e. how much an energy efficiency improvement is likely to actually reduce the heat consumption).

The cost-effectiveness of the aforementioned energy efficiency improvements is evaluated in the context of a district heating (DH) area. In Denmark, approximately 60% of residential buildings are currently connected to a district heating network which, from a private economic perspective, is among the heat supply options with the lowest cost. As a consequence, compared to other individual heat sources, investments in energy efficiency improvements are not always economically attractive, and the potential for cost-effective energy efficiency improvements is quite low. Previous studies in the literature, focusing on Danish cases, confirm the trend (Zvingilaite 2013; Zvingilaite and Balyk 2014; Zvingilaite and Klinge Jacobsen 2015). However, the future evolution of energy systems and the forecasted increase in fuel prices are expected to pose challenges for district heating networks. As a result, heat prices in district heating areas will likely rise, contributing to economically attractive energy efficiency improvements also in district heating areas. Furthermore, recent research studies have been focusing on the structure of the district heating tariffs in district heating, and its impact on motivating building owners to invest in economically optimal energy efficiency improvements. For instance, Djørup et al. (2020) highlight the potential of implementing a fully variable heat tariff scheme, which can improve the financial incentive for heat savings, while also making the system development less vulnerable to fluctuations and shortages in capital markets. Hvelplund et al. (2019) propose a 100% variable district heating tariff discussing challenges and benefits, while Sernhed et al. (2017) investigate, among others, the relation between the district heat tariff components and incentives to invest in energy efficiency.

An analysis of the cost-effective energy efficiency improvements potential for buildings in district heating areas, with a focus on details such as the heterogeneity of the building stock or the composition of district heating costs and tariffs, can thus facilitate the design of policies and actions that are tailored to specific buildings, tenants and technologies (Lechtenböhmer and Schüring 2011; Amoruso et al. 2018). On the contrary, a generalised approach might not work as efficiently and may lead to less desirable outcomes.

On these premises, this study develops estimates of technical and realistic heat-saving potentials and investigates the cost-effectiveness of investment in energy efficiency improvements from a private end-user perspective, focusing on a large sample of buildings connected in the district heating area of Aarhus in Denmark. A city with approximately 350,000 inhabitants.

The study investigates the following research questions: Does the inclusion of heterogeneous building characteristics, in the modelling of heat-saving, impact the identification of cost-effective energy efficiency improvements when considering the marginal costs of energy upgrading (i.e. the additional price when a renovation takes place anyway)? How does the cost-effectiveness of energy efficiency improvements relate to the energy efficiency of buildings? Is there an effect of exposing a private consumer to different heat tariffs, in relation to investments in cost-effective energy efficiency improvements?

The study contributes to the field by developing a methodology, incorporating the large heterogeneity of building characteristics, resulting in practical findings that can be useful for end-users, policy makers and district heating companies. By providing empirical results on the cost-effectiveness of heterogeneous energy efficiency improvements in residential buildings under different conditions, the paper broadens the knowledge on attractive residential energy efficiency improvements and on the influence of heat tariffs on cost-effective investments in energy efficiency improvements.

The remainder of the paper is organised as follows. Section "Method" presents the methodology, while Section "Data description" describes the case study, along with the data used, and contextualises the analysis. Section "Results" illustrates the results, which are further discussed in Section "Discussion". Last, Section "Conclusion and policy implications" concludes the study, reporting policy suggestions based on the findings.

Method

The study develops and employs two different methodologies. The first is used to evaluate technical and realistic energy efficiency improvements potentials, for a sample of buildings connected to a district heating area. On the basis of the data developed, the second method determines cost-effective investments in energy efficiency improvements, under different conditions.

Evaluating the technical and realistic energy efficiency improvement potentials in a heterogeneous building stock

The evaluation of the technical and realistic energy efficiency improvement potentials is performed through the method illustrated by Brøgger et al. (2018). By considering each building individually, the heterogeneity of the building stock can be encompassed. This can be done because the building's physical characteristics are available at the individual component level, as later described in Section "Data description".

The method consists of two steps: (1) calculation of energy demand and estimation of technical energy efficiency improvements and (2) Estimation of the realistic energy efficiency improvements.

1. In the first step, using a building physics–based model developed by Brøgger and Wittchen (2017), heat demands are calculated anew for each of the buildings considered. In this case, the energy consumption is studied at a whole building level (intended as a block of flats or a detached single-family house) rather than on a single unit level (e.g. an apartment), since potential energy efficiency improvements are often estimated at this level. The building physics–based model is based on the monthly mean calculation method (i.e. a quasi steady-state calculation) specified in EN ISO (2008). This entails that consumption profiles are not considered.

   By imposing hypothetical improvements, the model allows for estimating the technical potential for energy efficiency improvements in the building stock. This is done at the individual component level in each building, in order to capture the heterogeneity of building stock. Four building envelope components are considered for energy upgrading: roofs, floors, external walls and windows. In addition, the possibility of installing a mechanical ventilation system with heat recovery is considered. The energy efficiency improvements analysed in the study are described in detail in Section "Data description".

   By calculating the heat-saving potential of each component individually, the model also allows to evaluate several renovation levels (e.g. different insulation thicknesses for external walls) while considering the associated costs. The outcomes from the model are cost curves, which illustrate the cost of reducing the energy demand by a given amount (€/kWh), for each energy efficiency improvement, in each building. The aggregate effect of imposing several energy efficiency improvements is not included, as it is considered beyond the scope of this paper.

2. In the second step, the calculated heat demands are compared with the heat consumption registered in each building in a multiple linear regression model, i.e. a hybrid bottom-up building stock energy model (BSEM). The principle is illustrated in Fig. 1. By including additional details, such as information about the building type and energy performance certificate, etc., it is possible to adjust the gross (technical) potential and evaluate the net (realistic) potential for energy efficiency improvements. This implies having a more realistic estimation of the actual decrease in heat consumption. The evaluation of net improvements is performed to account for the "rebound effect", which hinders the realisation of the full technical potentials of energy efficiency improvements (Haas et al. 1998; Hens et al. 2010). In particular, consumers living in energy-efficient houses often use more energy in relation to the energy performance of the building, compared to residents living in energy-inefficient houses (Majcen et al. 2013). This suggests that heat savings achieved in practice, due to energy efficiency improvements, can be lower than those calculated in engineering conservation studies, causing an overestimation of the net heat savings (Majcen et al. 2016).

   As the literature reports several definitions of the rebound effect (Galvin 2014), we adopt the following definition of the rebound effects in the present study, to avoid ambiguity: The rebound effect ($R_\epsilon(E)$) is defined as the fraction of the technical (gross) potential that cannot be expected to be realised in practice. Mathematically, this can be expressed as

$$R_\epsilon(E) = 1 - \frac{\Delta C}{\Delta D} = \frac{\Delta D - \Delta C}{\Delta D} \tag{1}$$

   where ΔC is the realised change in consumption and ΔD is the expected change in consumption. This is equivalent to the definition of the energy saving deficit proposed by Galvin and Sunikka-Blank (2016).

The proposed definition of the rebound effect corresponds to estimating the slope of the regression line of the multiple linear regression model. Figure 1 proposes a graphical example.

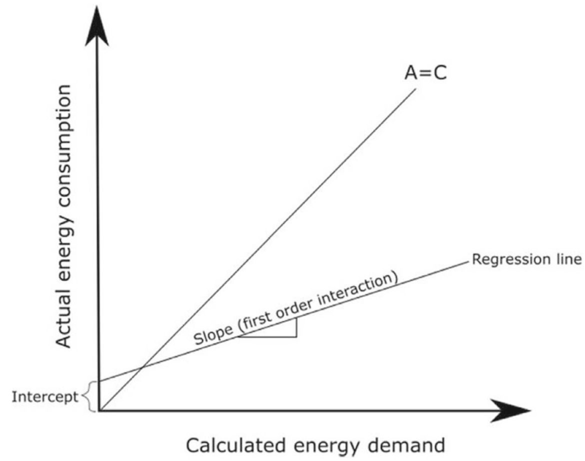

Fig. 1 The slope can be used for estimating the reduction in heat consumption given a reduction in heat demand due to an energy efficiency improvement (Brøgger et al. 2018)

In Fig. 1, the upper line represents the theoretical situation, in which the calculated energy demand (C) corresponds to the actual energy consumption (A), i.e. A=C (Theoretical). In this case, a one unit reduction in the calculated energy demand (because of an energy efficiency improvement) leads to the same unit reduction in the actual energy consumption. However, the real-data analysis shows that the relation is different and is mostly represented by the lower line (Actual). The slope of the line can thus provide indications about the actual impact of investing in an energy efficiency improvement, estimating the reduction in actual energy consumption given a reduction in the technical heat demand.

In practical terms, in a building-physical context, the rebound effects can be interpreted as heat savings that are exchanged for a better indoor climate, e.g. higher average indoor temperature, better air quality due to larger air change rates or the like. This implies that the full technical potential for energy efficiency improvements is not likely to be realised when a building is energy upgraded. According to the definition reported and in line with the example in Fig. 1, a unit reduction (technical potential) in the calculated energy demand, because of an energy efficiency improvement, leads to a smaller unit reduction (realistic potential) in the actual energy consumption. Following this logic, we identify both gross and net potentials for energy efficiency improvements.

Evaluating the cost-effectiveness of investments in energy efficiency improvements

The study analyses attractive energy efficiency improvements based on the net present value of cash flows, in line with other analyses (Baldini and Trivella 2017; Amstalden et al. 2007; Tommerup and Svendsen 2006; Gaterell and McEvoy 2005; Zvingilaite 2013; Zvingilaite and Klinge Jacobsen 2015). The study assumes the marginal cost of investment, that is the additional cost of investing in a more energy-efficient improvement, compared to the least performing improvement available, when renovation takes place. The extra investment cost c_i for a more efficient improvement i is compared with the expected economic saving resulting from the avoided heat consumption, throughout the lifetime of the energy efficiency improvement L_i. In this case, p^c is the cost of heat for a private Danish consumer connected to the district heating network, provided by local utilities.[1] The net present value (NPV) of investment is evaluated according to Eq. 2:

$$NPV1_i = -c_i + \left[\sum_{y=1}^{L_i+1} \frac{\alpha_y}{(1+\rho)^{y-1}} \left(p^c \, \xi_i^{max} \right) \right] \quad (2)$$

where p^c denotes the cost of heat in [€/MWh]. An investment is deemed cost effective in case of a positive net present value of cash flows. Equation 2 represents the trade-off between extra investment cost and cumulative annual saving. The expression inside brackets is the economic saving for the current year, calculated by multiplying the cost of heat with the consumption reduction ξ_i^{max}, achieved by investing in an energy efficiency improvement.[2] The expression is then summed over a number of years y corresponding to the lifetime of the energy efficiency improvement L_i, discounted according to a discount rate ρ and multiplied by a factor α_y indicating the expected change (increase or decrease) of heat costs for the year y. The NPV in Eq. 2 might differ from the conventional format, and this is due to three main assumptions:

- All investments are performed only at the beginning of the first year of the analysis.
- Economic savings, resulting from the investment in energy efficiency improvements, occur already in the investment year.
- The cash flow for the years after the investment year considers only positive revenues (i.e. no other costs are included after the investment).

Effects of changes in the tariff structure of district heating

For a private Danish consumer, district heating prices normally consist of a fixed and a variable part. The price of heat differs from one district heating area to another, in relation to the local conditions and generation costs (Danish Utility Regulator 2020). As investments in energy efficiency improvements reduce the need for heat for the building, the investment competes directly with the variable part of the cost of heat. To have an overview of the difference in costs between district heating areas in Denmark, Fig. 2 provides the share of the variable part of district heating prices. It is clear that the share of variable heat cost component differs considerably among areas.

Currently, in Aarhus, a building connected to district heating is subject to three cost components: consumption, capacity and subscription. The first, defined as p^c in Eq. 2, is a variable component in [€/MWh] and is proportional to the heat consumed. The second is a fixed component, in [€/m^2], and is related to the gross heated floor area of the building; the last component is also fixed [€] and represents the annual subscription cost for being connected to a district heating area (Danish Utility Regulator 2020). Figure 3 reports a graphical example. The colour coding relates to the nature of the cost components: the consumption fee is variable (green), meaning that it depends on the consumption of the building. The capacity payment is (almost) fixed (yellow), meaning that is a fixed fee for all buildings, a part from some which comply with certain characteristics. For the case of Aarhus, according to the 2015 regulations, this component can be halved either if the building was built after the Danish Building Regulation 2010 (BR 10) as low energy class

[1] The reader can refer to Section "DH tariff structure in Aarhus" for a thorough explanation of the heat cost p^c.

[2] This method assumes constant heat savings throughout the lifetime; hence, it disregards any deterioration of the performances in the long term or any changes in expected occupancy and use of the building, which could impact the level of heat savings (Eleftheriadis and Hamdy 2018).

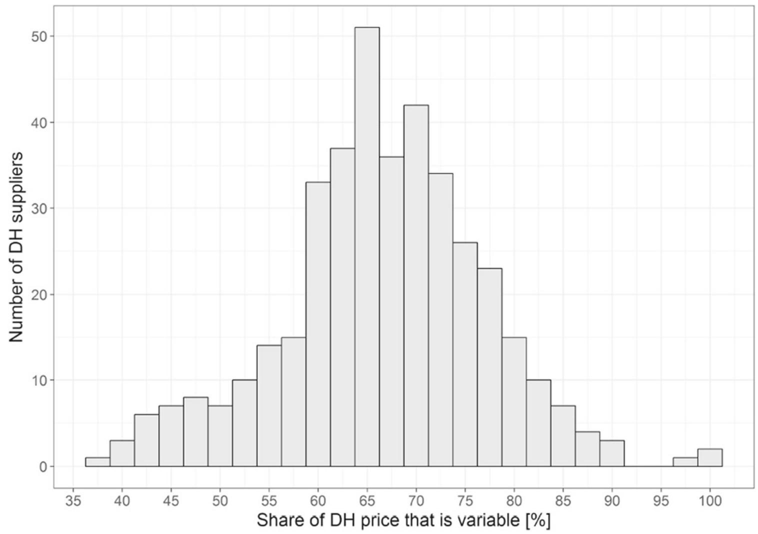

Fig. 2 Distribution shares of DH variable heat cost component (Danish Utility Regulator 2020)

2015 or if the building complies with the requirement for Energy Class 1 according to Building Regulations 2008 (BR 08) (Affaldvarme Aarhus 2018a; Trafik-, Bygge- og Boligstyrelsen 2018a).[3] Such arrangement can be considered as a reward for the "best energy performing building". Last, the yearly subscription is a fixed fee (red) which relates to the connection to the district heat network.

According to the current structure of the district heating tariff, the economic profitability of investing in an energy efficiency improvement, to reduce heat consumption, considers only the consumption component. From a building owner perspective, this implies lower incentives or motivation to invest, as the other two cost components are not affected by an eventual investment. Although straightforward, the reasoning locks out a wide range of potential energy efficiency improvements, which could become attractive if more heat cost components were variable. The cost-effectiveness of energy efficiency improvements could thus be enhanced by increasing the variable share of the DH price (i.e. making more parts of the price variable, to reflect better the cost of energy production). For example, if the heat tariff was structured in such a way to allow a reduction of the capacity payment, proportionally to the reduced heat consumption achieved by investing in a particular improvement, more energy efficiency improvements would result cost effective. This is relevant if savings actually could reduce future long-term capacity investments in the grid, for example, by reduced pipe dimensions or low temperature district heating. This can be seen as an extension of the discount on the capacity cost component, according to 2015 regulations, given compliance with the 2010 building regulation as low energy class 2015 (BR10) (Affaldvarme Aarhus 2018a).

The analysis could implicitly assume either that the current tariff components do not reflect real costs or that a fully variable district heating tariff scheme could improve the financial incentive for heat savings. Hence, allowing energy efficiency interventions to be rewarded through cost reductions could compensate for such discrepancy. Also, the method can be seen as a means to investigate how (and if) energy efficiency improvements could contribute to reducing long-term capacity costs in district heating grids.

Equation 2 is thus extended, to include the economic savings related with the capacity component, proportionally to the heat saved by the energy efficiency improvement i:

$$NPV2_i = -c_i + \left[\sum_{y=1}^{L_i+1} \frac{\alpha_y}{(1+\rho)^{y-1}} \left(p^c \, \xi_i^{max} + \frac{\xi_i^{max}}{q} \, p^{pg} \, \lambda \right) \right]. \tag{3}$$

In Eq. 3, q represents the heat consumption of the building in which the energy efficiency improvement

[3]The reader should be aware that such requirements, building regulation and related discounts are often updated, e.g. in 2018 (Affaldvarme Aarhus 2018a; Trafik-, Bygge- og Boligstyrelsen 2018a).

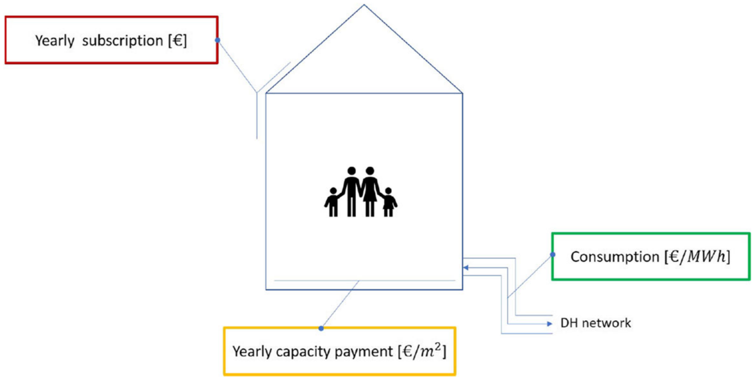

Fig. 3 District heating cost breakdown for end-user

can be implemented, p^{pg} the capacity cost component in [€/m^2] and λ the gross heated floor area of the individual building.

Last, the analysis considers an extreme case in which all heat cost components in the tariff are "variable", meaning that the investment cost is evaluated considering the consumption, capacity and subscription component at the same time. A similar approach has been also discussed in the research, e.g. by Djørup et al. (2020), Hvelplund et al. (2019), and Sernhed et al. (2017). Equation 3 is thus extended accordingly:

$$NPV3_i = -c_i + \left[\sum_{y=1}^{L_i+1} \frac{\alpha_y}{(1+\rho)^{y-1}} \left(p^c\, \xi_i^{max} + \frac{\xi_i^{max}}{q} p^{pg}\, \lambda + p^s \right) \right] \tag{4}$$

with p^s being the subscription cost component, in [€].

In practical terms, this means that by investing in enough energy efficiency improvements, the building could disconnect from the district heat network. In such situation, the building would save p^s [€] each year, as a result of not being connected to a district heating network (and thus not paying the subscription component). p^s would thus be a positive cash flow for each year [€/year] for the lifetime of the energy efficiency improvement. This could be considered as studying an extra-incentive for the building owner, to invest in energy efficiency improvement. The case implies two fundamental assumptions: (i) disconnecting from district heating supply is a valid possibility (nowadays, users are not allowed to disconnect from the district heating network that supplies heat to the building); and (ii) there is an alternative heat source which, after the implementation of the energy efficiency improvement, can supply the remaining heat demand at lower costs than district heating costs. Although the listed assumptions may not be currently realistic, pertinent actors in relevant institutions are discussing the possibility of re-thinking such policy, for a future where, e.g. district heating prices might increase (e.g. because of higher fuel costs).

Throughout the results, we refer to Eq. 2 for the *Base case*, Eq. 3 for the *Capacity reduction case (Cap.reduction)* and Eq. 4 for the *Total reduction case (Tot.reduction)*.

Data description

To ease an understanding of the assumptions behind the development of the gross and net potential for energy efficiency improvements, the section reports a description of the data: first presenting the technical characteristics about the building stock and the energy efficiency improvements considered, after, introducing details about the district heating tariff in Aarhus.

Building and energy efficiency improvement characteristics

The main data source for the analysis is the Danish energy performance certificate (EPC) database developed at Aalborg University, in Denmark (Brøgger and Wittchen 2016). The energy performance certificate is a label evaluating the energy efficiency (or performances) of a building, rated on a scale from A2020 (most efficient) to G (least efficient). The data include details about the building (e.g. year of construction, heat supply, building type and energy performance certificate) and about physical characteristics (e.g. areas and U-values) of building components (i.e. walls, roofs) of each individual building. The geographical location and the annual heat consumption from the past 3 to 5 years, registered by utility companies, are also available for all buildings.

The dataset includes 12,589 residential buildings connected to the district heating network in Aarhus, corresponding to a coverage of 18.6% of the building stock relying on the same district heating network.

The sample is compared with the building stock of the city of Aarhus, in terms of construction year, to verify that the data available closely match the reality. The year of construction, as well as the specific grouping, is used as a proxy for the energy efficiency of the buildings (evaluated in terms of energy performance certificate), in line with Kragh and Wittchen (2014). The sample distribution is displayed in Table 1 and is deemed fairly representative. Some differences compared to the national statistics hold, but overall are acceptable.

In terms of heat demand, Fig. 4 illustrates gross values for the sample, calculated according to Brøgger et al. (2018). In total, the gross heat demand amounts to 541.1 GWh, while the corresponding net heat demand to 437.8 GWh.

As the dataset available allows to access the physical characteristics of each building component for each of the buildings, it is possible to develop energy efficiency improvements tailored to the characteristics of the actual buildings, without using synthetic archetypes.

The energy efficiency improvements considered for energy upgrading the building envelope include roofs, floors, external walls, and windows. In addition, the possibility of installing a mechanical ventilation system with heat recovery is also examined as an energy efficiency improvement.

On these bases, Table 2 lists, by number and type, the components available for energy upgrading according to the respective energy performance certificate (EPC) of the buildings.[4] The values presented are the result of the method proposed in Section "Evaluating the technical and realistic energy efficiency improvement potentials in a heterogeneous building stock".

In line with other studies, the lifetime of the energy efficiency improvements is assumed to be 60 years for external walls, 60 years for floors, 40 years for roofs, 40 years for ventilation systems and 30 years for windows (Trafik-, Bygge- og Boligstyrelsen 2018b; Wittchen et al.2017).

Energy efficiency improvements considered

To assess the cost-effectiveness of energy upgrading each component individually (i.e. walls, roofs), in terms of potential energy efficiency improvements and related costs, the study considers marginal costs of investments (i.e. the additional cost of investing in a more energy-efficient improvement, compared to the least performing improvement available, when renovation takes place). Hence, the price of scaffolding, etc. are not included in the price, which thus only include the material costs.

With respect to the energy efficiency improvements considered, the analysis is based on the following assumptions:

- Regarding external walls, the study considers only exterior re-insulation, as interior re-insulation requires a case-specific assessment of the moisture conditions, to avoid problems with mould growth. Particularly, although there exist different insulation options (e.g. exterior re-insulation, interior re-insulation or cavity wall insulation for hollow walls), only exterior re-insulation of massive external walls and cavity wall insulation (i.e. hollow external walls) is considered, since the price of insulating the two are substantially different.
- All roofs are assumed to be identical, i.e. no distinction is made between flat roofs and gable roof (i.e. roofs with a slope) because this information is not available from the dataset. This can result in an impact on the maximum possible insulation thickness, which is thus not considered. However, as this only applies to the most ambitious energy efficiency improvements (i.e. the largest insulation thicknesses), it should not affect the results considerably.
- As with roofs, no distinction is made between different types of floors (e.g. crawl-spaces, cellars, etc.), in terms of costs assumed.

[4]Clarification note: the values represent energy upgrading opportunity elements (energy efficiency improvements). For instance, considering that there is a total of 12.6 K buildings, and 77.5 K energy efficiency improvements as external walls, on average there are 77.5/12.6≃6.2 external wall renovation opportunities for every building. Nonetheless, differences apply for various building categories.

Table 1 Share of buildings by year of construction: survey sample and city of Aarhus

Year of construction	<1890	1890–1929	1930–1949	1950–1959	1960–1972	1973–1978	1979–1998	1999–2006	>2006
Sample (%)	2.9	15.0	11.5	8.9	20.0	9.2	18.3	5.9	8.3
Aarhus (%)	2.5	11.9	9.6	8.4	21.4	12.0	20.4	7.3	6.4

– Two types of windows are considered in this study: 2-pane (energy class B) and 3-pane (energy class A) windows. For the analysis, the cost of replacing a window is considered as the full price. As a consequence, windows are an expensive component material-wise, e.g. in comparison with insulation. The assumption holds as, hypothetically, the price of the least energy-efficient window could have been assumed to be zero, if these were to be replaced by the end of their service life. However, as all other energy efficiency improvements can be employed without replacing them (e.g. an external wall could be re-insulated without replacement), this cannot be the case for windows.
– Lastly, mechanical ventilation is considered as an energy efficiency improvement, because of the possibility of heat recovery. The price of installing a mechanical ventilation system is assumed to be fixed per unit area. No distinction is thus made between different building types, nor sizes. However, it could be that the installation of a mechanical ventilation system would depend on the size and geometry of the building (e.g. the number of floors).

It should be noted that, as architectural concerns are not considered, some energy efficiency improvements may not be implemented, even though they turn out to be cost effective, e.g. because a facade is worthy of preservation. The characteristics of the eligible energy efficiency improvements are listed in Table 3.

As insulation batches normally come in predefined thicknesses, only standard thicknesses available in the market are considered; hence, the step-wise increase in insulation thicknesses. Table 3 lists the eligible energy efficiency improvements and the associated costs of adopting a particular level of an energy efficiency improvement, with price values according to Molio.dk (2018).

The "Level" column specifies the technical properties of the energy efficiency improvements, e.g. the insulation thickness to be added to the existing construction (or the energy class, for windows). The λ value specifies the assumed thermal conductance of the insulation material. Likewise, the U-value denotes

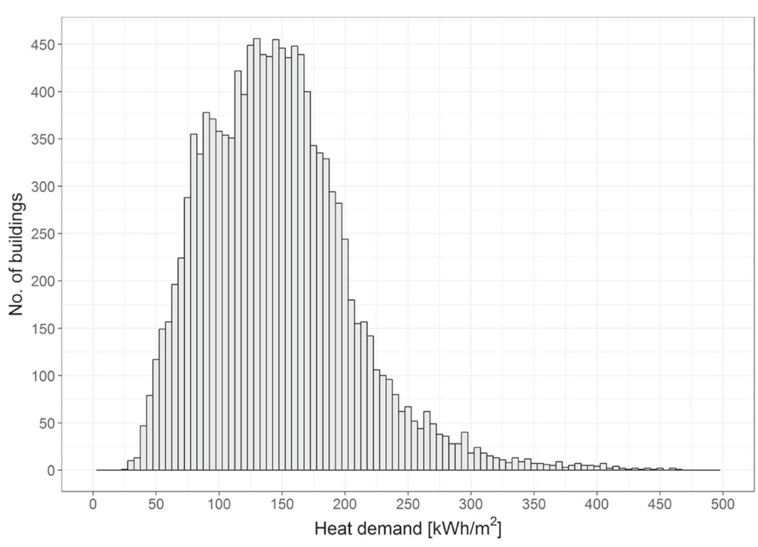

Fig. 4 Calculated gross heat demand of the considered building stock

Table 2 Summary table for dataset under investigation (EEI = energy efficiency improvements)

	EPC									Total
	A2020	A2015	A2010	B	C	D	E	F	G	(K units)
No. of buildings	12	71	373	1505	3482	3886	2011	867	382	12.6
Share (%)	0.1	0.6	2.9	11.9	27.6	30.9	15.9	6.9	3.1	100%
No. of EEI										
External walls	72	426	2238	9030	21000	23840	12678	5616	2636	77.5
Floors	36	213	1116	4512	10443	11661	6033	2601	1146	37.8
Roofs	48	284	1492	6020	13928	15548	8044	3468	1528	50.4
Ventilation	11	70	295	1244	2991	3395	1686	707	296	10.7
Windows	139	650	3636	15474	39124	50895	29064	13610	6022	158.6
Share of total EEI by EPC	0.1%	0.5%	2.6%	10.8%	26.1%	31.4%	17.2%	7.8%	3.5%	100%

the thermal properties of the windows, while η is the efficiency of the heat recovery in the mechanical ventilation system.

The "Costs" column specifies the marginal costs of adopting the corresponding level of energy efficiency improvement, i.e. the additional costs (e.g. + 7.1 €/m^2), compared with the previous level (e.g. 13.6 €/m^2). For windows, the replacement cost is assumed to be the full price of the window as a component, with costs based on Molio.dk (2018). However, it should be taken into account that the cost of a window is related both to the area and to the thermal standard (i.e. energy class). To this end, to link standard values to the windows' characteristics available from the dataset, we considered the price of a number of windows with the corresponding size; Fig. 5 illustrates the concept. On the basis of the size and the class, using a linear regression model, the price of the windows from

Table 3 Eligible energy efficiency improvements

Component	Level	Costs	Note
Roof	+ 95 mm	13.6 €/m^2	$\lambda = 0.37$
Roof	+ 145 mm	+ 7.1 €/m^2	
Roof	+ 195 mm	+ 6.8 €/m^2	
Roof	+ 240 mm	+ 5.1 €/m^2	
Floors	+ 145 mm	55.2 €/m^2	$\lambda = 0.37$
Floors	+ 170 mm	+ 2.6 €/m^2	
Floors	+ 195 mm	+ 1.2 €/m^2	
Ext. walls (cavity)	+ 80 mm	23.6 €/m^2	$\lambda = 0.37$
Ext. walls (cavity)[a]	+ 130 mm	+ 6.9 €/m^2	
Ext. walls	+ 125 mm	202 €/m^2	
Ext. walls	+ 200 mm	+ 43 €/m^2	
Ext. walls	+ 250 mm	+ 37 €/m^2	
Windows	Energy class B	Area-dependent[b]	U-value = 1.4
Windows	Energy class A		U-value = 0.9
Mechanical ventilation	-	80.4 €/m^2	$\eta = 0.85$

[a]In the study, the full price of implementing cavity insulation was considered, as cavity insulation is a binary choice: either insulate the entire cavity and only what is possible for your building or do not insulate. Therefore, the additional costs listed in the "Costs" column is the price difference between the two cavity insulation options rather than a marginal cost

[b]See description in the text along with Fig. 5

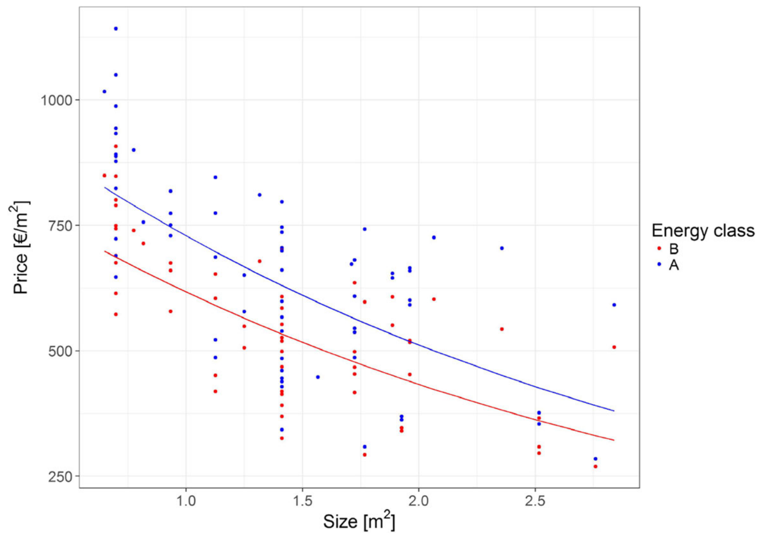

Fig. 5 Window price depending on the size of the window

the dataset is estimated for each element, according to its characteristics.

Considering these assumptions, the study developed cost curves for all the energy efficiency improvements, tailored to the characteristics of the buildings. The cost curves are employed to assess cost-optimal levels of investments, according to the methods presented in Section "Evaluating the cost-effectiveness of investments in energy efficiency improvements". As an example, Fig. 6 provides an overview of the cost curves for external walls (i.e. marginal cost of investments vs cumulative heat savings), based on all the buildings available. Although some categories are overlapping, it results clear that energy efficiency improvements for cavity walls insulation possess a considerably larger cost-effective potential, compared to energy efficiency improvements for exterior insulation.

DH tariff structure in Aarhus

As illustrated in Section "Evaluating the cost-effectiveness of investments in energy efficiency improvements", the district heating price in Aarhus is based

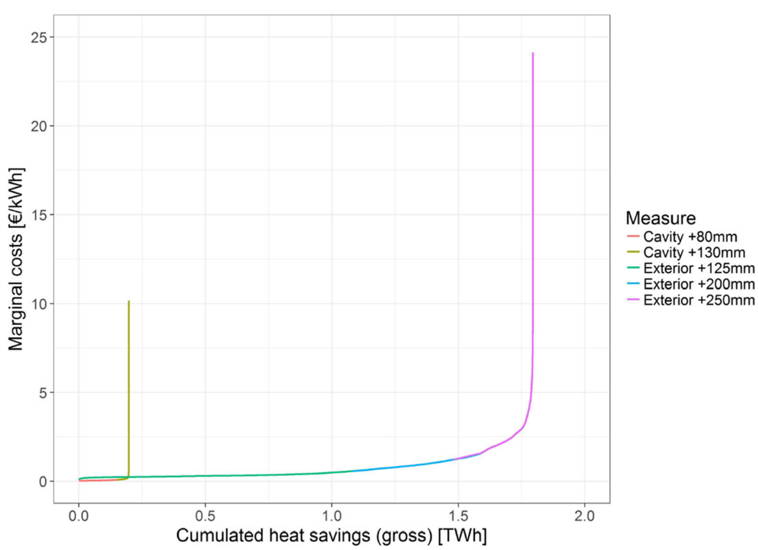

Fig. 6 Example of heating cost curves: external walls

on three components: a consumption fee (variable, in [€/MWh]), a capacity fee (fixed, [€/m^2]) and a subscription fee (fixed, [€]). The analysis considers cost components according to the 2015 tariffs, as reported in Table 4, and assumes constant values throughout the horizon of the investigation. The values are set to reflect cost components, including capacity, and are approved by local regulatory authorities.

Case study and sensitivity analysis

In relation to the case study, the cost-effectiveness of investments in energy efficiency improvements is investigated according to a *Base case*. At first, only the variable heat cost component is considered and a discount rate of 5% for residential investments is assumed. Nowadays, the risk-free investment rate in Denmark is very close to zero (Danmark National-Bank 2020). However, to account for the expected uncertainty from investments (given, e.g. fuel price volatility and regulatory uncertainty), investor socioeconomic conditions (e.g. income, education, age) and risk attitudes, a conservative approach is adopted. This is in line with studies focusing on investments of heat savings in the Danish residential building sector (Ben-Amer-Allam et al. 2017; Zvingilaite 2013); other studies also suggest to use a discount rate within the range 3–6% for private investors in the household sector (Steinbach and Staniaszek 2015; Hermelink and De Jager 2015).

To consider uncertainties related to relevant input data, a sensitivity analysis is performed: first, acting on the discount rates, evaluating the outcomes with 3% and 7% discount rates, and after, acting on the structure of the district heating tariff, according to the logic presented in Eqs. 3–4, to explore the effect of varying heat tariffs on the overall uptake of energy efficiency improvements.

Table 5 summarises the input data employed for each case; for the heat costs, the values refer to Table 4.

Table 4 Heat tariffs for the district heating area of Aarhus, 2015 (Affaldvarme Aarhus 2018a)

Consumption (€/MWh)	Capacity (€/m^2)	Subscription (€)
86.43	2.44	126.63

Results

Base case

Preliminary check The main driver for the investment lies in the economic profitability of adopting a particular energy efficiency improvement, based on the cumulative heat savings achieved during its entire lifetime, because of the avoided heat consumption. To get the first idea of potentially attractive investments, we calculate the average energy per unit that could be saved each year if an investment of 1 € was made in one of the examined energy efficiency improvements. The outcomes in Fig. 7 highlight that, on average, the annual economic savings are more attractive for external walls (EW), floors (FL) and roofs (RO), while investments in windows (WI) and ventilation (VE) are the least beneficial. Based on the data available, it also results that kWh/€ invested are higher for buildings with lower energy labels (see, e.g. E, F, G). The results are different for gross and net potentials. Although Fig. 7 gives an overview of the potential benefit related to different investments, the most cost-effective energy efficiency improvements also depend on the characteristics (e.g. area) and the related economic/heat savings.

Cost-effective cost curves Figure 8 illustrates the resulting cost curves for attractive energy efficiency improvements, identified according to the method in Section "Evaluating the cost-effectiveness of investments in energy efficiency improvements". The outcomes remark the difference between the gross (right side) and net energy efficiency improvements (left side), highlighting a larger cost-effective potential for the first (around 50 GWh) compared to the second (around 9 GWh) approach. The most expensive cost-effective energy efficiency improvements for both curves top at a marginal cost of around 1.7 €/kWh. The total cost-effective energy efficiency improvements correspond to 9.3% and 1.9% of the total gross and net heat consumption from all the buildings. In total, energy efficiency improvements resulted attractive in 8074 (gross) and 2034 (net) buildings, with average heat savings/building around 6.23 MWh and 4.11 MWh respectively.

Typologies of energy efficiency improvements in total cost-effective investments Figures 9 and 10 report

Table 5 Case study and sensitivity analysis description

Case name	Discount rate	Cost components considered		
		Consumption	Capacity	Subscription
Base case	5%	✗		
DR 3%	3%	✗		
DR 7%	7%	✗		
Cap. reduction	5%	✗	✗	
Tot. reduction	5%	✗	✗	✗

the typologies of cost-effective energy efficiency improvements, i.e. showing how much each energy efficiency improvement contributes to the total heat savings, according to building category EPC (Energy Performance Certificate). Two key points are to be considered: the heterogeneity of cost-effective energy efficiency improvements in building categories and the difference between technical (gross) and realistic (net) potentials.

The outcomes for gross potentials show that floors (FL) and roof (RO) constitute the majority of attractive investments among all the categories, followed by external walls (EW). Ventilation (VE) and windows (WI) contribute only in part. For the net potentials, Fig. 10 shows that roofs and external walls are the predominant attractive investments for building categories C-D-E-F-G (see, e.g. the size of the related bars). On the other hand, windows appear as the optimal investments for buildings with high energy performances (A2015-A2010-B); in two cases (i.e. A2015-A2010), windows are the only attractive investment, as the reader can also see from Table 6. Furthermore, Fig. 10 shows that investments in ventilation are not deemed attractive and there are no cost-effective energy efficiency improvements for buildings in category “A2020”, for the the case of net savings.

Table 6 reports the total GWh heat savings resulting from attractive investments, according to the energy efficiency improvement type and energy performance certificate labels of the buildings (EPC). Although we

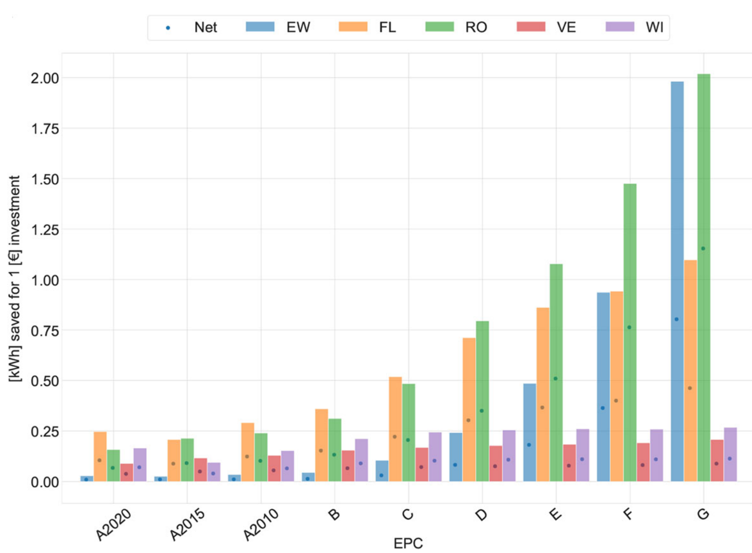

Fig. 7 Average kWh/year saved for 1 € invested in building envelope component, for building categories EPC (Energy Performance Certificate)

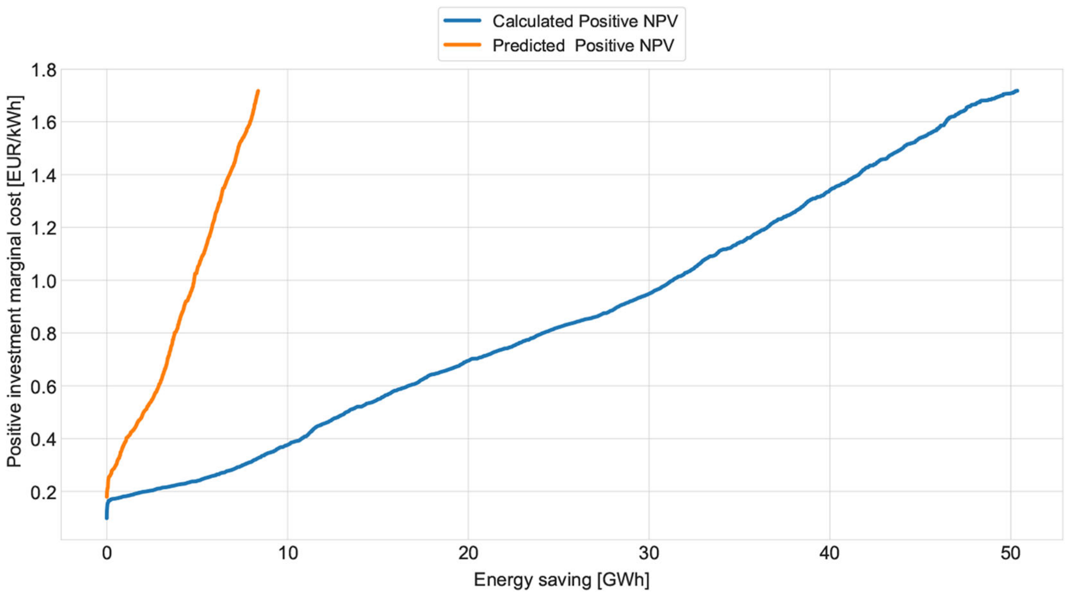

Fig. 8 Cost curves for cost-effective investments in energy efficiency improvements. The orange line denote the net potential, whereas the blue line denote the gross potential

cannot generally compare the absolute values among building categories due to original differences in the sample data,[5] the difference between the gross and net saving potentials is noticeable. Table 6 shows that attractive investments in building category A2020, already at low levels for the gross potentials approach, are null for the case of net potentials. Also, most of the energy efficiency improvements are present in buildings with EPC D and E for the gross potentials, while the net approach shows a redistribution of attractive investments, which are more present in building category E and F. One can also notice the relevant change of scale among the two approaches highlighting that, overall, total attractive energy efficiency improvements are consistently lower for net potentials by a factor 6.

Sensitivity analysis

The variation of the outcomes is investigated according to the parameters presented in Table 5. Figure 11 presents the total amount of heat savings achieved with cost-effective investments, for the different cases. For a discount rate of 3%, the total attractive potential amounts to 95 GWh and 12.6 GWh, for the gross and net approach. For a discount rate of 7%, the total amounts to 38 GWh for gross potentials and 6.2 GWh for net potentials.

For the cases where the tariff structure is varied, the total cost-effective investments increase considerably, reaching gross heat savings around 69 GWh (11 GWh, net) for the “Cap-reduction” case and 96 GWh (22 GWh, net) for the “Tot. reduction” case. By allowing the capacity heat cost component to be variable, increases of almost 37% (gross) and 26% (net) are observed compared to the base case.

To assess in detail the variations of investments for the various cases, we consider the payback period (PBP) (defined as the time required for the investment to break-even), as it provides a simple base of comparison with the expected lifetime of the corresponding energy efficiency improvement. Theoretically, attractive investments will show values of payback periods lower than the lifetimes of energy efficiency improvement. In practice, consumers would probably require payback times to be shorter than 8–15 years, unless they include an increase in property value, for example, resulting from a change in energy certificate, or if they approach investments with a green/environmental

[5] Observing the values in Table 6, it would seem obvious that buildings with EPC label D and E have the largest potential for attractive investments; however, this is due to the distribution of energy efficiency improvements among buildings, presented in Table 2, which is indeed biased.

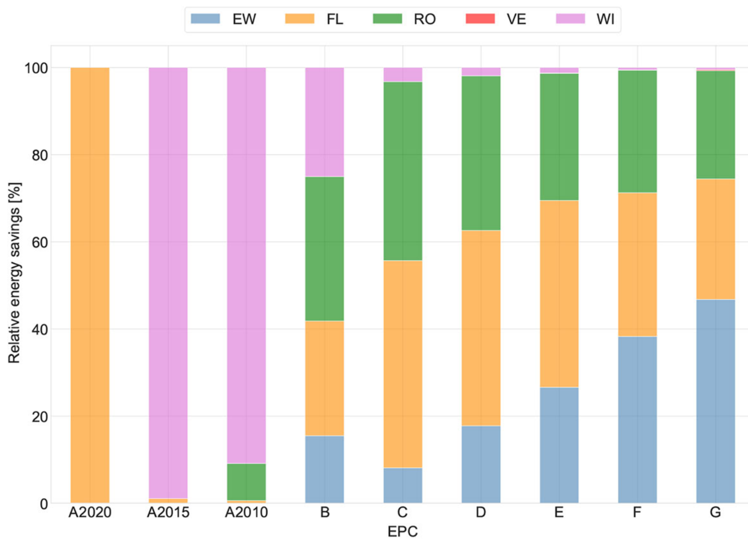

Fig. 9 Typologies of energy efficiency improvements in total cost-effective investments by EPC (%), gross potentials

attitude (Baldini and Trivella 2017; Baldini et al. 2018). Figure 12 illustrates the sensitivity performed: the green bar identifies the lifetime, while the black and red markers identify the resulting PBPs, for the gross and net potentials. The results represent an average over all the attractive energy efficiency improvements from the base case, investigated under different conditions.

For the gross potentials (black markers), Fig. 12 shows that two scenarios influence most the attractiveness: DR 7% and Tot. reduction. Assuming a discount rate of 7% leads to non-attractive investments for almost all the building components, a part from external walls (EW) and roofs (RO), as the payback period extends over the lifetime. On the other hand, the "Tot. reduction" scenario, where it is assumed that all heat-cost components are variable, leads to a consistent decrease in the value of the average payback period. The net potentials case (red markers) presents similar results, a part from ventilation (VE), which is not attractive. The outcomes highlight that the methodology applied is most sensitive to the "DR 7%" and "Tot.

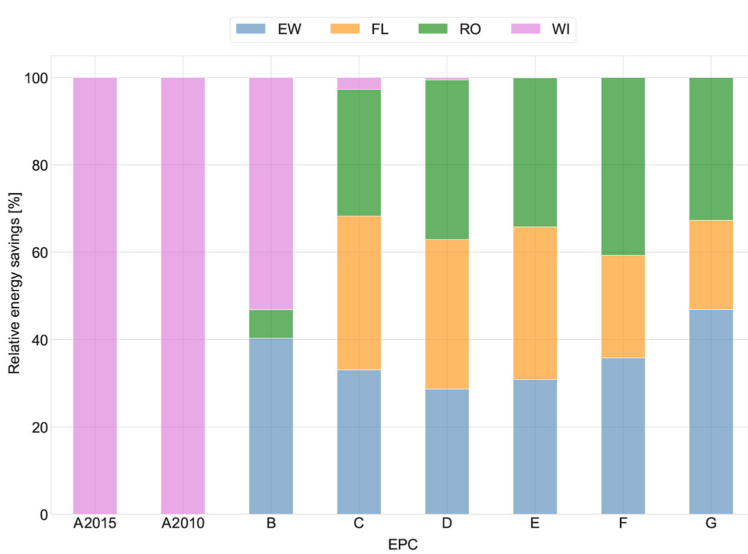

Fig. 10 Typologies of energy efficiency improvements in total cost-effective investments by EPC (%), net potentials

Table 6 Summary table for attractive investments in energy efficiency improvements by building envelope component and energy performance certificate (EPC); gross and net potentials (GWh)

Component	External wall		Floor		Roof		Ventilation		Windows		Total	
	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net
EPC												
A2020	0	0	0.001	0	0	0	0	0	0	0	0.001	0
A2015	0	0	0.001	0	0	0	0	0	0.005	0.001	0.005	0.001
A2010	0	0	0.001	0	0.001	0	0	0	0.019	0.005	0.020	0.005
B	0.010	0.003	0.017	0	0.022	0.001	0	0	0.016	0.004	0.066	0.007
C	0.288	0.060	1.692	0.063	1.461	0.052	0	0	0.115	0.004	3.557	0.181
D	2.643	0.556	6.672	0.663	5.283	0.709	0	0	0.284	0.010	14.883	1.938
E	3.963	0.793	6.391	0.897	4.346	0.879	0.012	0	0.191	0.001	14.905	2.572
F	3.833	0.716	3.305	0.468	2.815	0.815	0.007	0	0.056	0	10.017	1.999
G	3.227	0.782	1.907	0.340	1.715	0.546	0.015	0	0.035	0	6.901	1.669
Total	13.966	2.912	19.986	2.433	15.645	3.003	0.035	0	0.724	0.026	50.359	8.375

reduction" scenario; the other two cases seem to have a lower impact on the base case results, with quite some closeness between each other.

Table 7 reports a summary, highlighting the increase (+%) or decrease (−%) in the number of attractive energy efficiency improvements (N°) and on the average value of the payback period (PBP), comparing the sensitivity cases with the base case. For instance, assuming a discount rate of 3% leads to an increase of 90% in the number of attractive investments in external walls; at the same time, the average payback period, for the same sample of energy efficiency improvements which were attractive in the base case, decreases of about 27%.

Effects of exposing a private consumer to a larger share of variable costs

To investigate the effects of varying heat cost components, the sensitivity analysis focuses on two details: the heterogeneous distribution of heat cost components among buildings and the effect of having a

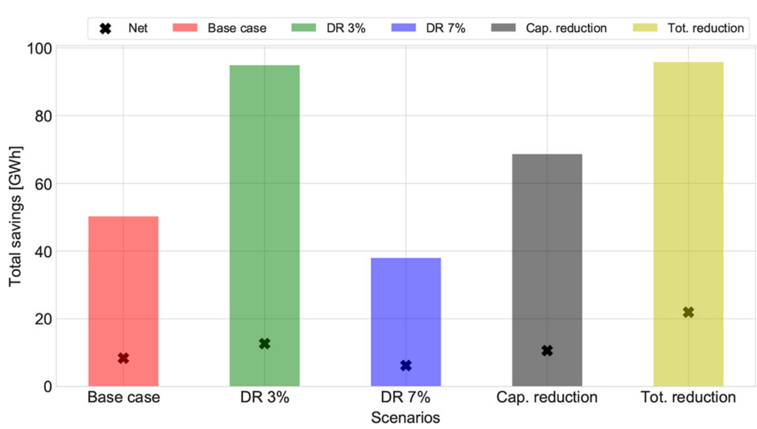

Fig. 11 Total heat savings per scenario as a result of cost-effective energy efficiency improvements (GWh)

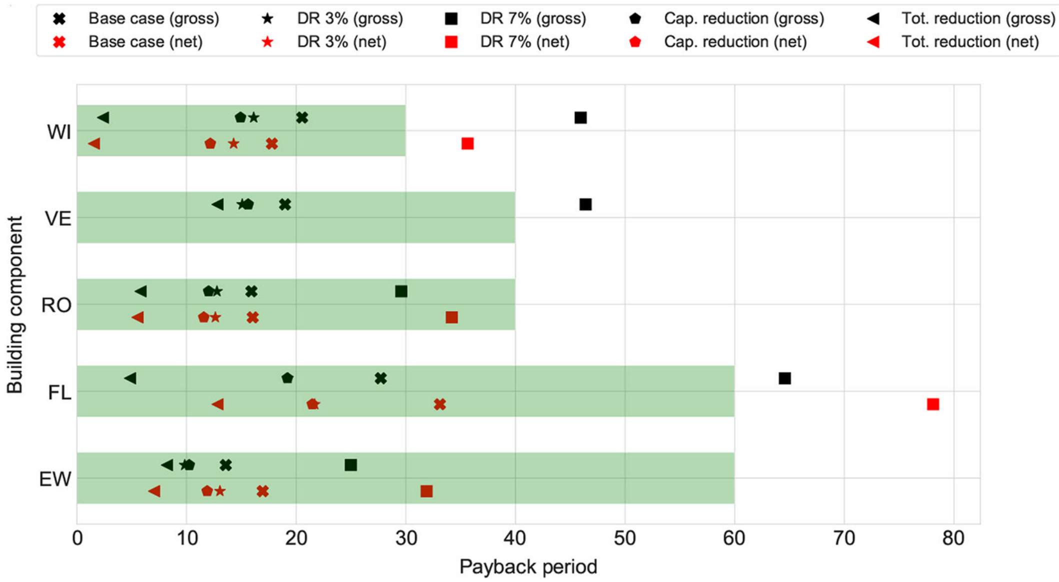

Fig. 12 Average payback period of cost-effective energy efficiency improvements, by building component [Years]. The green bars denote the assumed lifetime of each component

larger share of variable costs. Figure 13 reports, on the basis of the building characteristics, the average share of costs per heat cost component by building category. The red bars identify how much, on average, a building spends in relation to the heat consumption component; the green bars show how much buildings pay for the capacity component, and the light yellow bars identify expenses related to the subscription component. The results highlight heterogeneity among building categories. Buildings with the best energy performances (e.g. A2020, A2015 and A2010) have most of the costs related with capacity and subscription (i.e. fixed costs), while buildings with the worst energy performances (e.g. E, F, G) have more costs linked with consumption component (i.e. variable costs).

Following the considerations reported in the method section, on the basis of these cost distribution, the sensitivity analysis investigates the contribution of tariffs component to total attractive investments, in a tariff structure with a larger share of variable costs.

Figure 14 shows the share of cost-effective investments in relation to each heat cost tariff components, that is how many investments would take place because a particular heat cost component is made variable. The outcomes in Figs. 13 and 14 are linked. For buildings with the highest EPCs, which present an average lower heat consumption, there is a larger

Table 7 Relative changes (%) for the simulated scenarios compared to base case, gross potentials

	Base		DR3% (%)		DR7% (%)		Cap.red.(%)		Tot.red.(%)	
Component	N°	PBP	N°	PBP	N°	PBP	N°	PBP	N°	PBP
Ext. wall	1161	13.5	+90	−27	−18	+84	+33	−24	+ 224	−39
Floor	6750	27.7	+48	−30	−44	+133	+35	−30	+ 86	−82
Roof	4875	15.9	+23	−19	−20	+85	+16	−24	+ 153	−63
Ventilation	3	18.9	+267	−20	−33	+144	+200	−17	+ 1567	−32
Windows	1423	20.5	+173	−21	−57	+123	+138	−27	+10172	−88

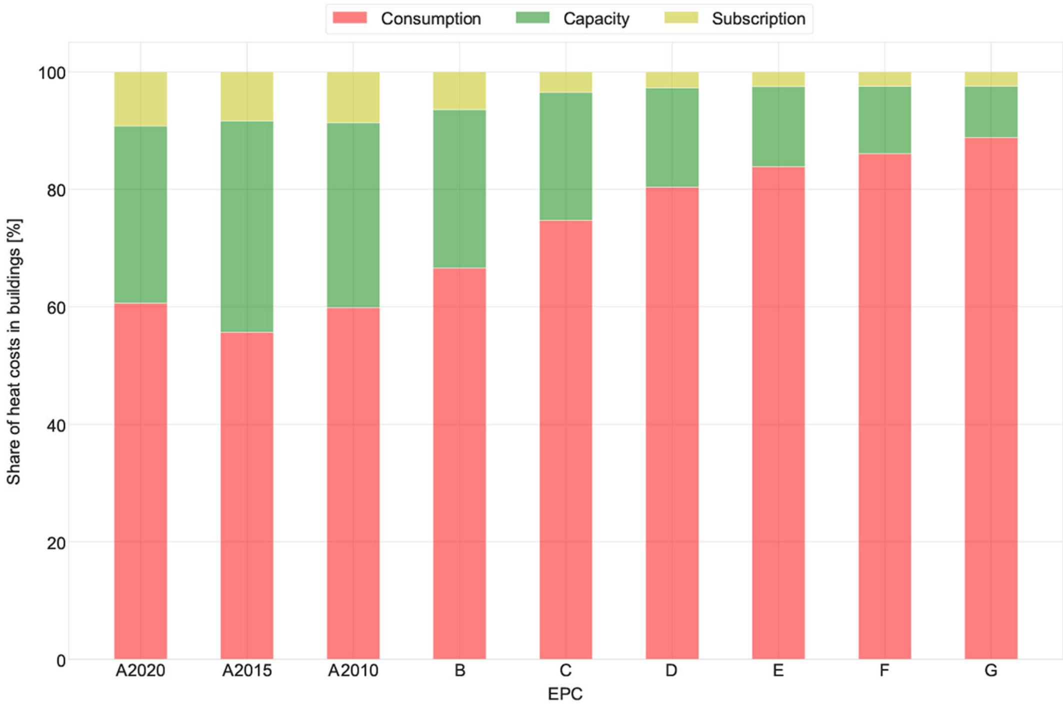

Fig. 13 Share of heat costs in building by EPC category (Energy Performance Certificate), based on sample data available

Fig. 14 Share of cost-effective investments in relation to the heat cost tariff components, by EPC category

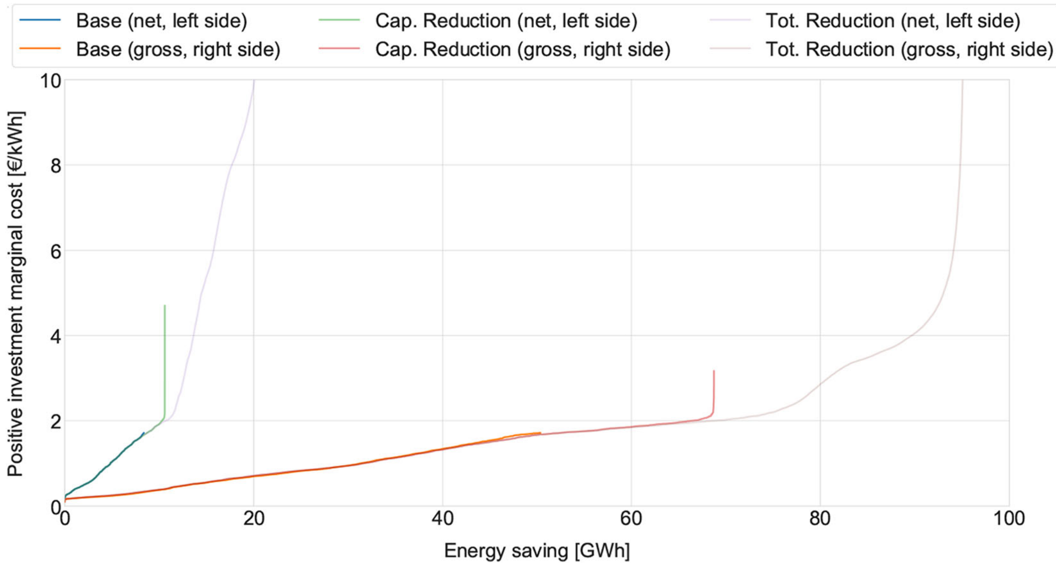

Fig. 15 Cost curves for the cost-effective energy efficiency improvements, according to heat cost components and gross/net cases

incentive to invest in energy efficiency improvements if the subscription component is variable (yellow bars). On the other hand, for buildings with lower EPCs, which have an average larger heat consumption, there is a larger incentive to invest in relation to the consumption and capacity component (red and green bars).

Last, Fig. 15 shows the cost curves for the energy efficiency improvements deemed worthy of investment (i.e. cost effective) according to the methodology provided in Section "Evaluating the cost-effectiveness of investments in energy efficiency improvements", by heat cost components (Base, Cap. reduction, Tot. Reduction) and net/gross cases. The curves illustrate the cumulative sum of the heat savings (GWh) from all the cost-effective investments, arranged according to the marginal cost of investments in €/kWh, from the cheapest to the most expensive. The curves thus display what are the cost levels (€/kWh) of reducing the energy demand by a given amount (GWh), for the total heat savings reported in Fig. 11, as a result of the cost-effective energy efficiency improvements.[6]

[6]For instance, notice that the total savings for the "Base (net, left side)" curve in Fig. 15 (i.e. the end of the line) are the same as the one reported in Fig. 11 for the "Base Case (Net)" column: 8.3 GWh.

The outcomes in Fig. 15 show that exposing the private consumer to a larger share of variable costs (the heat tariff components) can unlock a wider range of attractive energy efficiency improvements, available at different marginal costs according to the case considered, and with a remarkable difference between attractive gross (technical) and net (realistic) potentials.

Discussion

On the quest of investigating attractive investments in energy efficiency improvements to reduce heat consumption for a heterogeneous set of buildings, the study employs different methodologies to develop gross (technical) and net (realistic) potentials. According to the rich details available in the dataset, the models calculate building-tailored options for energy upgrading the building envelope. In addition to the energy efficiency improvements considered for the study, interior insulation could also offer a way of energy upgrading the building envelope, given that moisture conditions allow for doing so. This would increase the potential for energy efficiency improvements. On the other hand, neglecting architectural concerns (e.g. facades worthy of preservation) and assuming no physical restrictions on roof insulation (e.g. limited attic space) could likely decrease the potential, leading to a possible overestimation of the results.

A detailed assessment of the cost-effective energy efficiency improvements in the building stock, which can facilitate the estimation and realisation of such potential according to heterogeneous building characteristics, was performed. The heterogeneous outcomes show fundamental differences in regard to gross and net potentials, which translates in distinct levels of cost-effective energy efficiency improvements according to building characteristics. Energy efficiency improvements such as external walls, floors and roofs are found to contribute the most to the total stock of cost-effective investments, while mechanical ventilation and windows are found to be less relevant. This is in line with the preliminary check performed in Fig. 7, where we investigated the average heat savings per unit of investment, although the share of investments by EPC differs compared to the levels illustrated. The outcomes are aligned with other studies investigating on the Danish building stock, a part from investments in windows (Zvingilaite 2013; Zvingilaite and Balyk 2014; Zvingilaite and Klinge Jacobsen 2015). Indeed, for windows, it was assumed full cost of investments, as usually they are physically replaced at the moment of renovation (compared for instance to walls or roofs, which are extended with additional layers). This assumption probably limited attractiveness. Differently from other studies, the study assesses the attractiveness of heterogeneous energy efficiency improvements tailored to building characteristics, without using archetypes, and linking investments with energy performance certificates (EPC) of the buildings. The analysis highlights a rich diversity among cost-effective energy efficiency improvements, both in terms of numbers and type, which would have been disguised if average costs and potentials were used. This also allows to assess the distribution of attractive energy efficiency improvements among building categories, easing the development and design of policies, e.g. rebates or subsidies, for particular energy efficiency improvements.

For instance, analysing the outcomes in Table 6, it results that most of the energy efficiency improvements are cost effective for buildings with low energy performance classes: out of the total 50.35 GWh, resulting from attractive investments in the gross potential case, only 0.01 GWh are related to buildings with EPC A2020-A2015-A2010-B. Likewise for net potentials. Also, as the investments deemed worthy represent only a small fraction of the total potentials available, meaning that many other energy efficiency improvements are yet to be attractive,[7] subsidies for investments in energy efficiency improvements should be directed unevenly throughout building categories, mostly targeting residents in buildings with EPCs D to G where most of the unexploited potentials still lay. Last, as the outcomes revealed that overall some energy efficiency improvements are more attractive than others, policy support should be directed to the category with the lowest investments. For instance, the results in Figs. 9 and 10 and Table 6 suggest that windows and mechanical ventilation are non-attractive options for buildings with low energy performances, while the opposite is valid for buildings with high energy performances. Likewise, external walls and floors seem to dominate cost-effective investments in low energy performing buildings, while the opposite is not true for buildings with high energy performances. The outcomes highlight that a heterogeneous approach can reveal attractive options, which would have been disguised with the use of archetypes. Considering that Danish energy supply companies are required to implement energy efficiency improvements as long as cost effective (Forsynings og Klimaministeriet 2015; Forsygnings og Klimaministeriet 2018), the approach can surely supply more specific indications on attractive options.

The sensitivity analysis performed on discount rates, which have a major role in determining the economic incentives for building renovations and energy efficiency improvements (Djørup et al. 2020; Mata et al. 2015), has highlighted key findings. Compared to the base case, assuming a discount rate of 3%, which in practical terms could represent the point of view of a risk-taker investor (Steinbach and Staniaszek 2015; Hermelink and De Jager 2015), leads to a 90% increase in the total GWh of heat savings from attractive energy efficiency improvements. On the other hand, a discount rate of 7%, which could reflect the attitude of a risk-averse investor (i.e. an investor which is financially concerned about the future value of investment), leads to a 24% decrease. Figure 12 also proved that lower discount rates can induce shorter

[7]Compare the number of potential investments in Table 2 and the number of cost-effective investments in Table 6.

payback periods, allowing a faster recovery of investments, differently for each energy efficiency improvement. A lower discount rate can be related to lower taxation rates on loans from banks or other institutions; thus, local authorities in Aarhus, aiming at fostering the uptake of energy efficiency improvements in the residential sector, should ease the burden of loans for renovation purposes, offering lower interest rates.

Last, the outcomes of the study spark suggestions about relevant policy measures in regard to potential changes in the district heating tariff structures and their impact on motivating building owners to invest in economically optimal energy efficiency improvements. The sensitivity analysis shows that when all the cost components are made variable, the related investments in energy efficiency improvements distribute unevenly among building categories based on the energy performance certificates (EPC) (see Fig. 14). For buildings with high EPCs, most of the investments happen in relation to the subscription component while for buildings with low EPCs, most of the investments are related to the consumption and capacity components. Intuitively, the best energy performing buildings, with low energy consumption, present most of the attractive investments in relation to the subscription component which, ultimately, would imply a disconnection from the district heating grid. On the other hand, buildings with low energy performances would not find a hypothetical disconnection relevant, but they would benefit from a tariff that rewards the investments in energy efficiency improvements.

Although advantageous from an investor perspective, such hypothetical heat tariff structure can arise implications at the energy system scale for the district heating (DH) companies. A reduction in the capacity costs can have negative implications for the DH company, which has based its asset and investments on a plan of cost recovery. Hence, a decrease in the capacity component could hit the revenues of the company, which ultimately might not be able to fully recover the costs. Moreover, for this tariff to work, the peak consumption of the building would need to decrease, as the DH company would set its operation network to satisfy the newly reduced heat demand.

On the other hand, the application of this method can lead to positive implications for the DH producers, similarly to what Djørup et al. (2020) and Hvelplund et al. (2019) have also investigated. Indeed, if the overall demand for the building stock decreases and the energy efficiency improvements implemented allow the building to reduce losses, the district heat network could start to supply heat at lower temperatures. This shift would imply lower heat transmission losses and would facilitate the integration of renewable energy sources as supply options. As investments in energy efficiency improvements would take place on a long time period, the transition would give time to the DH companies to adjust the plans and operation of the asset, eventually planning ahead for new investments in lower temperature networks or adapting the current network to the new needs, highlighting a synergistic effect between energy efficiency improvements and DH supply. It is worth to mention that eventual changes in policies towards carbon emission reduction, targeting combined heat and power plants or heat generation systems, will probably lead to an overall increase of the heat prices. This scenario will most likely favour additional investments, broadening the volume of cost-effective energy efficiency improvements.

Conclusion and policy implications

In Europe, the residential building stock holds a large potential for energy efficiency improvements, to reduce heat consumption, related to energy upgrading of the building envelope. Energy efficiency in buildings is expected to play a key role in future energy scenarios, reducing energy consumption, the related greenhouse gas emissions and, consequently, the impact of the building sector on climate change. This study designs methods to analyse costs and potentials for heterogeneous building-tailored energy efficiency improvements and evaluate their cost-effectiveness. Based on a large building sample, investments are evaluated for a district heating area in Denmark, as expected future changes in heat prices could lead to additional economically attractive options.

The study is novel and significant as it develops a method to calculate tailored energy efficiency improvements, using actual building characteristics and not synthetic archetypes, which are often employed for assessing the potentials and can lead to loss of diversity or miscalculation in the real potential (Wittchen et al. 2017; TABULA Project Team 2012). Individual buildings that are relatively energy efficient may thus include some attractive options that are not revealed when using archetypes. Furthermore, the study accounts for building-tailored rebound effects and develops both technical (gross) and more realistic (net) potentials, allowing a more accurate analysis of attractive energy efficiency improvements.

The study analyses attractive energy efficiency improvements for a private end-user based on the net present value of cash flows, comparing investments with the cost of heat consumption over a lifetime. The analysis also investigates the sensitivity of the results to changes in the input parameters, focusing on the effect of different district heating tariffs structures, on the total cost-effective investments.

In the base case, the gross and net heat savings, resulting from investments in attractive improvements, sum up to 50.4 GWh and 8.4 GWh, corresponding to 9.3% and 1.9% of the current total gross and net heat demand. Although the attractive potential does not represent a large share, the study highlights the need for considering rebound effects (i.e. distinguishing technical and realistic potentials) and the modelling of building-tailored energy efficiency improvements, rather than using archetypes. The outcomes show that cost-effective energy efficiency improvements vary considerably among building groups with different energy performances (EPC). In particular, a large share of the potentials are attractive for energy-inefficient buildings (e.g. EPC D through G).

When all the tariff components are variable, a considerable increase in the total cost-effective potential is observed, with specific energy efficiency improvements distributed unevenly among building EPCs categories. Different tariff policies could thus be applied to motivate building owners to invest in economically optimal energy efficiency improvements. The cost components provide different incentives to invest, according to EPC building categories. If investments in energy efficiency improvements can potentially reduce the future long-term capacity investments in district heating grid (entailing a reduction of the heat-costs), part of the investments should be passed as an incentive to the district heating customer.

The presented study could be extended in several directions. From a building perspective, a natural extension would be to increase the temporal resolution of the model, considering heat demand profiles (e.g. peak loads). Another option could be to link attractive energy efficiency improvements with energy systems analysis, to investigate the energy system impact of changes in heat demand and alternative heat sources. In relation to this, the work should also focus on future projections of district heating costs.

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