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Cost-effectiveness of building heat-saving measures in a Danish district heating area

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Abstract

The residential building stock holds a large saving potential related to energy-upgrading of the building envelope. Heterogeneous details about building characteristics are paramount to perform a proper assessment of attractive heat-savings measures. Based on a sample of buildings, the study develops methods to identify saving potentials for heterogeneous building-tailored heat-saving measures 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 heat-saving measures. The analysis is novel as it rely on modelling actual 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 results sensitivity to assumption about the discount rate and focuses on the effect of different district heating tariffs, on the total cost-effective investments. The outcomes show that cost-effective measures vary considerably, in size and type, among building categories, based on energy performances certificate labels (EPC). When all the cost components are variable, the total cost-effective potential increases considerably, with specific measures distributed differently among building categories, with the cost components providing different incentives to invest. Heterogeneity thus does matter, when evaluating economically attractive investments in heat-saving measures.

Keywords: Cost-effective heat-saving measures, heterogeneous building characteristics, district heating tariffs, energy performance certificates,

rebound effects.

1. 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, as they account for approximately 40% of the total energy consumption in the EU (European Commission, 2018).

The low energy efficiency of the (aging) building stock make buildings a target for energy upgrading, aiming at reducing their energy consumption. 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.

In the residential sector, the consumer can decide to invest in heat-saving measures -such as windows, insulation of walls, floors or ceilings-aiming at improving the heat performance of the building. From an economic perspective, the attractiveness of saving options can be evaluated comparing investment costs and resulting savings with the costs of the heat supply replaced. 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 measure 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 an heterogeneous approach is often preferred when assessing building heat-saving options, the literature shows that it is challenging to develop tailored data for large existing building stocks and validate them against real measurements. Bottom-up building physics-based models are mostly used for this purpose, as they allow to assess the energy-saving potential given an energy-upgrade of building components, e.g. roofs or external walls (Kragh and Wittchen, 2014). 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 use building archetypes (i.e. synthetic/average buildings), for assessing the energy-saving potentials (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 a measure, e.g. if the actual energy-performance of a particular building was different from the archetype.

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 heat-saving measures (e.g. windows, external walls, roofs,...), 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-conservation measure is likely to actually reduce the heat consumption).

The cost-effectiveness of the aforementioned measures 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, options for heat-saving investments are not always economically attractive, and the potential for cost-effective heat-saving investments 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 forecasted fuel prices, are expected to pose challenges for district heating networks, for example considering the reduced heat supply from combined heat-and-power plants which may lose their competitiveness in the electricity market. As a results, heat prices in district heating areas will likely rise, contributing to economically attractive heat-saving options also in district heating areas. An analysis of the cost-effective heat-saving potential of 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. 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 on the cost-effectiveness of investment in heat-saving measures from a private end-user perspective, focusing on a large sample of buildings connected in the district heating area of Aarhus, in Denmark. The study investigates on the following research questions: Does inclusion of heterogeneous building characteristics, in the modelling of heat-saving, impact the identification of cost-effective measures? How are the optimal savings distributed over the existing energy efficiency classifications for buildings? Is there an effect of exposing a private consumer to different heat tariffs, in relation to investments in cost-effective heat-saving measures?. 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 cost-effectiveness of heterogeneous heat-saving measures in residential buildings under different conditions, the paper broad-

ens the knowledge on attractive residential heat-savings and on the influence of heat-tariffs on cost-effective heat-saving investments.

The remainder of the paper is organised as follows. [Section 2](#) presents the methodology, while [Section 3](#) describes the case study and contextualise the analysis. [Section 4](#) illustrates the results, which are further discussed in [Section 5](#). Last, [Section 6](#) concludes the study, reporting policy suggestions based on the findings.

2. Method

The study develops and employs two different methodologies. The first is used to evaluate technical and realistic heat-saving 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 heat-saving measures, under different conditions.

2.1. Evaluating technical and realistic heat-saving potentials

The evaluation of the technical and realistic heat-saving potentials is performed through the method illustrated by [Brøgger et al. \(2018\)](#).

The method consists of three steps: 1. calculation of energy demand (and estimation of technical heat-savings); 2. identification of the relation between calculated energy demand and actual (observed) energy consumption; 3. estimation of realistic heat-savings.

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. For 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 heat-savings are often estimated at this level. As the building-physics based model is based on the monthly mean calculation method specified in [EN ISO \(2008\)](#), consumption profiles are not considered. Given the

heterogeneity of building characteristics available, the model allows to estimate values of technical heat-saving potentials, for instance computing changes in the calculated energy demand, following an hypothetical implementation of an heat-saving measure, according to the physical characteristics of each component in a specific building. Four building envelope components are considered for energy upgrading: roofs, floors, external walls and windows. Additionally, the possibility of installing a mechanical ventilation system with heat recovery is considered. By calculating the heat-saving potential of each component individually, the model also allows to evaluate several option for renovations (e.g. different insulation thicknesses for external walls), in combination with the associated costs, simultaneously. The outcomes from the model are cost curves, illustrating the cost (€/kWh) of reducing the energy demand by a given amount, for each heat-saving measure, in a specific building.

2. The heat demands calculated during the first step are then compared with the registered consumption in the same individual buildings. The comparison highlighted dissimilarities among the two demands with, in general, an overestimation of the calculated consumption. Several studies have already identified such *performance gap*, i.e. a discrepancy between the energy demand calculated in a building-physics based model and actual household energy demand. 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 heat-saving measures, can be lower than those calculated in engineering conservation studies, causing an overestimation of the *net* heat-savings (Majcen et al., 2016). Implicit factors, such as rebound and pre-bound behaviour by the inhabitants or building thermal characteristics after an energy upgrade, can be identified as responsible for the discrepancy. The second step thus consist in identifying the relation between the calculated energy demands (computed with the model presented in Step

1) and the actual energy consumption (available from registered consumption) in individual buildings. Figure 1 illustrates the logic. The upper line represent the theoretical situation, in which the calculated energy demand (C) correspond to the actual energy consumption (A), i.e. $A=C$ (Theoretical). In this case, a unit reduction in the calculated energy demand (because of a heat-saving measure) 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 heat-saving measure, estimating the reduction in actual energy consumption given a reduction in the technical heat demand. Using the multiple linear regression model proposed by Brøgger et al. (2018) and based on the data available on building characteristics, it is thus possible to compute the regression line (or slope) for each building under analysis and adjust the technical potential for heat-savings ¹.

3. Based on the outcomes from Step 1 and 2, by means of a multiple linear regression model considering multiple factors (e.g. the energy-performance or type of building), it is possible to adjust the gross (technical) potential and evaluate net (realistic) heat-saving potentials. This imply having a more realistic estimation of the actual decrease in heat consumption. The evaluation of net savings is performed to deal with the "rebound effect", which hinders the realization of the full technical potentials of saving investments (Haas et al., 1998; Hens et al., 2010). As the literature reports several definitions (Galvin, 2014), to avoid ambiguity, we hereby present the adopted approach to represent rebound effects for the present study: *The rebound effect ($R_{\epsilon}(E)$) is defined as the fraction of the technical (gross) potential, which could not be expected to be realised in practise.* According to the definition, and in line with the model presented in Step 2,

¹For the details about regression coefficients, dependent and independent variables assumed, please refer to the original paper by Brøgger et al. (2018).

the realistic (net) heat-saving potential is considered relative to the technical (gross) heat-saving potential (i.e. as a percentage). Mathematically, this could be written as:

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

where ΔC is the realised change in consumption and ΔD is the expected change in consumption. This is equivalent to the definition proposed by [Galvin and Sunikka-Blank \(2016\)](#). 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 imply that the full technical potential for heat-savings is not likely to be realised when a building is energy upgraded. According to the definition reported and in line with the example reported in [Figure 1](#), a unit reduction (technical saving potential) in the calculated energy demand, because of a heat-saving measure, leads to a *smaller* unit reduction (realistic saving potentials) in the actual energy consumption. Following to this logic, we identified both gross and net heat-saving potentials.

Figure 1: The slope can be used for estimating the reduction in heat consumption given a reduction in heat demand due to an heat-saving measure ([Brøgger et al., 2018](#)).

2.2. Evaluating cost-effective investments in heat-saving measures

The study analyse attractive heat-saving measures based on 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). The study assumes marginal cost of investment, that is the additional cost of investing in a more energy efficient measure, compared to the least performing measure available for renovation. The assumption relates to the long-term perspective on investments, and assumes that renovation in the building occurs at some point on time. Consequently, the study disregard the reasons and the timing that move the investor to perform building renovation. The extra investment cost c_i for a more efficient measure i is compared with the expected economic saving resulting from the avoided heat consumption, throughout the lifetime of the measure. The Net Present Value (NPV) of investment is evaluated according to Eq.(2):

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

where p^c denotes the cost of heat in [€/MWh]. An investment is deemed cost-effective in case of positive net present value of cash flows. Eq.(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 heat cost with the consumption reduction ξ_i^{max} , achieved by investing in a saving measure ². The expression is then summed over a number of years y corresponding to the lifetime of the measure 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 .

²This method assumes constant 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 savings (Eleftheriadis and Hamdy, 2018).

2.3. Effects of changes in the tariff structure of district heating

For a private Danish consumer, district heating prices normally consists 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, 2018). As investments in heat-saving measures reduce the need of heat for the building, the investment competes directly with the variable part of the cost of heat. To have an overview on the difference in costs between district heating areas in Denmark, Figure 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.

Figure 2: Distribution shares of DH variable heat cost component (Danish Utility Regulator, 2018).

Currently, in Aarhus, a building connected to district heating is subject to three cost-components: consumption, capacity and subscription. The first is a variable component, in [€/MWh]), and is proportional to the heat consumed. The second is a fixed component, in [€/m²], 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, 2018). 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 fixed fee for all buildings, a part from some which comply with certain characteristics. For the case of Aarhus, according to the regulations, this component can be halved either if the building was built after BR 10 as low energy class 2015/2020 or if it was built after BR 15 (Affaldvarme Aarhus, 2018). 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.

Figure 3: District heating cost breakdown for end-user.

According to the current structure of the district heating tariff, the economic profitability of investing in a heat-saving measure 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 heat-saving potentials, which could become attractive if more heat-cost component were variable. The cost-effectiveness of heat-saving measures 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 savings achieved by investing in a particular measure, more heat-saving measures would result cost-effective. This can be seen as an extension of the existing possibility of obtaining a discount on the capacity cost, given compliance with the 2015 building regulation (BR15) (Affaldvarme Aarhus, 2018).

The analysis could implicitly assume that the current tariff components do not reflect real costs. Hence, allowing savings interventions to be rewarded through cost reductions, could compensate for such discrepancy. Also, the method can be seen as a mean to investigate how (and if) savings could contribute to reduce long-term capacity costs.

Eq.(2) is thus extended, to include the economic savings related with the capacity component, proportionally to the heat saved by measure i :

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

In Eq.(3), q represents the heat consumption of the building in which the measures can be implemented, p^{pg} the capacity cost-component in [$\text{€}/m^2$] and λ the gross heated floor area of the individual building.

Last, the analysis considers an extreme case in which all heat-cost components are variable. Eq.(3) is thus extended accordingly:

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

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

In practical terms, this means that by investing in heat-saving measures, the building could disconnect from the district heat network. 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 saving measure, 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 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)*.

3. Data description

To ease an understanding of the assumptions behind the development of gross and net heat-savings, the section reports a description of the data: first presenting the technical characteristics about the building stock and the heat-saving measures considered; after, introducing details about the district heating tariff in Aarhus.

3.1. Buildings and heat-saving measures characteristics

The main data-source for the analysis is the Danish energy performance certificate (EPC) database developed at Aalborg University. 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,...), tailored to each building. The geographical location and the annual heat consumption from the past three to five years, registered by utility companies, is 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.

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

In terms of heat demand, [Figure 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.

Figure 4: Calculated gross heat demand of the considered building stock.

As the data-set available allows to access the physical characteristics of each building component for each of the buildings, it is possible to develop heat-

saving measures tailored to the characteristics of the actual buildings, without using synthetic archetypes.

Four building envelope components are considered for energy upgrading: roofs, floors, external walls and windows. The possibility of installing a mechanical ventilation system with heat recovery is also examined as a saving measure.

On these basis, [Table 2](#) lists the components available for energy-upgrading according to the respective energy performance certificate (EPC) of the buildings³.

Table 2: Summary table for dataset under investigation.

	EPC									Total (K units)
	A2020	A2015	A2010	B	C	D	E	F	G	
N°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%
N°of measures										
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 measures by EPC	0.1%	0.5%	2.6%	10.8%	26.1%	31.4%	17.2%	7.8%	3.5%	100%

In line with other studies, the lifetime of the heat-saving measures 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, 2018](#); [Wittchen et al., 2017](#)).

³Clarification note: the values represent energy-upgrading opportunities elements (measures). For instance, considering that there is a total of 12.6 K buildings, and 77.5 K external walls measures, on average there are $12.6/77.5=6$ external wall renovation opportunities for every building. Nonetheless, differences apply for various building categories.

3.2. Heat-saving measures considered

To perform an assessment of the cost-effectiveness of energy-upgrading each component individually, in terms of potential heat-savings and related costs, the study considers marginal costs of investments. Hence, wages, price of scaffolding, etc. are not included in the prices, which thus only include the material costs.

With respect to the heat-saving measures 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 measures (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.
- 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; replacement of windows may thus not be considered as cost-effective as energy-upgrading other components. The assumption hold as, hypothetically, the price of the least energy-efficient window could have been assumed to be zero, if these were to be replace by the end of their service lift. However, as all other heat-saving measures could 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 heat-saving measure, 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 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 heat-saving measures 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 heat-saving measures 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 heat-saving measures and the associated costs of adopting a particular level of a measure, with price values according to [Molio.dk \(2018\)](#).

The *Level* column specifies the technical properties of the measures, 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 the thermal properties of the windows, while η is the efficiency of the heat recovery in the mechanical ventilation system.

⁴See description in the text along with [Figure 5](#).

Table 3: Eligible heat-saving measures.

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)	+ 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 ⁴	U-value = 1.4
Windows	Energy class A		U-value = 0.9
Mechanical ventilation	-	80.4 €/m ²	$\eta = 0.85$

The *Costs* column specifies the marginal costs of adopting the corresponding level of a measure, i.e. the additional costs (e.g. + 7.1 €/m²), compared with the previous level (e.g. 13.6 €/m²). 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 to 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 data-set, we considered the price of a number of windows with the corresponding size; [Figure 5](#) illustrates the concept. On the basis of the size and the class, using a linear regression model, the price of the windows from

the data-set is estimated for each element, according to its characteristic.

Figure 5: Window price depending on the size of the window.

Considering these assumptions, the study developed cost curves for all the heat-saving measures, 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 Subsection 2.2. As an example, Figure 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 measures for cavity walls insulation possess a considerably larger cost-effective heat-saving potential, compared to measures for exterior insulation.

3.3. DH tariff structure in Aarhus

As illustrated in Subsection 2.2, the district heating price in Aarhus is based on three components: a consumption fee (variable, in [€/MWh]), a capacity fee (fixed, [€/m²]) and a subscription fee (fixed, [€]). The analysis considers cost

Figure 6: Example of heating cost curves - External walls.

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.

Table 4: Heat tariffs for the district heat area of Aarhus, 2015 ([Affaldvarme Aarhus, 2015](#)).

Consumption	Capacity	Subscription
[€/MWh]	[€/m ²]	[€]
86.43	2.44	126.63

The price/MWh of the consumption component in the district heating area of Aarhus, is among the lowest compared to other areas in Denmark. On the other hand, the costs related with the variable heat cost component correspond to 84.3% of the total average expenses in a 130m² single-family house with an annual heat demand of 18.1 MWh, which is among the largest shares compared with other DH areas, as reported in [Figure 2](#) ([Affaldvarme Aarhus, 2018](#)).

3.4. Case study and sensitivity analysis

In relation to the case study, the cost-effectiveness of investments in heat-saving measures 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. The value could be perceived as large, considering that in Denmark the risk-free investment rate is about 3%. However, to account for the expected uncertainty from investments (given e.g. fuel price volatility and regulatory uncertainty), investor socioeconomic conditions and risk attitudes, a conservative approach is adopted. Hence the discount rate of 5%.

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. 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 heat-saving measures.

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

Table 5: Case study and sensitivity analysis description.

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

4. Results

4.1. Base case

Preliminary check. The main driver for the investment lies in the economic profitability of adopting a particular measure, based on the cumulative savings

achieved during its entire lifetime, because of the avoided heat consumption. To get a 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 measures. The outcomes in Figure 7 highlight that, on average, the annual savings are more attractive for external walls (EW), floors (FL) and roofs (RO), while investments in windows (WI) and ventilation (VE) measures 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 savings potentials. Although Figure 7 gives an overview of the potential benefit related with different investments, the most cost-effective measure also depend on the characteristics of the measures (e.g. area) and the related savings.

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

Cost-effective cost curves. Figure 8 illustrate the resulting cost curves for attractive heat-saving potentials. The outcomes remark the difference between the gross (right side) and net savings (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 measures for both curves top at marginal cost around 1.7 €/kWh. The total cost-effective savings corresponding to 9.3% and 1.9% of the total gross and net heat consumption from all the buildings. In total, heat-saving measures resulted attractive in 8074 (gross) and 2034 (net) buildings, with average savings/building around 6.23 MWh and 4.11 MWh respectively.

Figure 8: Cost curves for cost-effective investments. The orange line denote the net, whereas the blue line denote the gross heat-saving potential.

Contribution of measures to total cost-effective investments. Figure 9 and Figure 10 report the contribution of measures to total cost-effective investments, i.e. showing how much each measure contributes to the total savings, according to building category EPC (Energy Performance Certificate). Two key points are to be considered: the heterogeneity of cost-effective measures in building categories and the difference between technical (gross) and realistic (net) savings.

Figure 9: Composition of measures for total cost-effective investments [%], gross saving potentials.

The outcomes for gross saving 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) measures contribute only in part. For the net saving potentials, [Figure 10](#) shows that roofs and external walls are the predominant attractive investments, followed by floors and windows. For this case, investments in ventilation are not deemed attractive and there are no cost-effective measures for buildings in category "A2020".

Figure 10: Composition of measures for total cost-effective investments [%], net saving potentials.

Table 6 reports the total GWh savings resulting from attractive investments, according to measure type and energy performance certificate labels of the buildings (EPC). Although we cannot generally compare the absolute values among building categories due to original differences in the sample data⁵, the difference between the gross and net saving potentials is noticeable. Table 6 shows that attractive heat-saving investments in building category A2020, already at low levels for the gross approach, are null for the net savings case. Also, most of the savings are present in buildings with EPC D and E for the gross savings, 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

⁵Observing 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 measures among buildings, presented in Table 2, which is indeed biased.

attractive savings are consistently lower for net saving potentials by a factor 6.

Table 6: Summary table for attractive heat-saving investments by building envelope component; gross and net saving potentials [GWh].

Component	External wall		Floor		Roof		Ventilation		Windows		Total	
	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net
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

4.2. Sensitivity analysis

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

For the cases where the tariff structure is varied, the total cost-effective heat-saving potential increases considerably, reaching gross 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, an increase of almost 37% (gross savings) and 26% (net savings) is observed compared to the base case.

Figure 11: Total savings per scenario [GWh].

To assess in particular the variations of investments for the various cases, and particularly to study the impact on the individual measures, we consider the pay-back 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 measure. Attractive investments will show values of pay back periods lower than the lifetimes of the measure. Figure 12 illustrate the sensitivity performed: the green bar identifies the lifetime, while the black and red markers identifies the resulting PBPs, for the gross and net savings approaches. The results represent an average over all the attractive measures from the base case, investigated under different conditions.

Figure 12: Average pay-back period of cost-effective heat-saving measures, by building component [Years]. The green bars denote the assumed lifetime of each component.

For the gross savings case (black markers), Figure 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 pay-back 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 pay-back period. The net savings case (red markers) presents similar results, a part from ventilation measures (VE), which are not attractive. The outcomes highlight that the methodology applied is most sensitive to the "DR 7%" and "Tot. 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 measures (N°) and on the average value of the pay-back 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 pay-back

period, for the same sample of measures which were attractive in the base case, decreases of about 27%.

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

Component	Base		DR3% (%)		DR7% (%)		Cap.red.(%)		Tot.red.(%)	
	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

4.3. 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 larger share of variable costs. [Figure 13](#) reports, on the basis of the building characteristics, the average share of costs per heat-cost components by building categories. The red bars identify how, on average, a building spend in relation to heat consumption component, the green bars show how much buildings pay for the capacity component, and the light yellow bars identify expenses related with 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).

Figure 13: Share of heat costs in building categories EPC (Energy Performance Certificate), based on sample data available.

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

Figure 14: Share of cost-effective investments in relation to the heat-cost tariff components.

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 Figure 13 and Figure 14 are linked. For buildings with the highest EPCs, which present an average lower heat consumption, there is a larger incentive to invest in heat-saving measures 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).

Figure 15: Effects of variable heat-cost components on total cost-effective heat-saving measures.

In absolute terms, Figure 15 illustrates that exposing the private consumer to a larger share of variable costs, can unlock a wider range of attractive heat-saving measures. The curves show that cost-effective investments can be attractive with different levels of marginal costs according to the case considered, with a remarkable difference between attractive gross (technical) and net (realistic) heat-saving potentials.

5. Discussion

On the quest of investigating the attractive heat-saving investments for an heterogeneous set of measures and buildings, the study employs different methodologies to develop gross (technical) and net (realistic) heat-saving potentials. According to the rich details available in the dataset, the models calculates building-tailored options for energy-upgrading the building envelope. In addition to the measures considered for the study, interior insulation could also offers a way of energy-upgrading the building envelope, given that moisture conditions allow for doing so. This would increase the potentials of heat-savings. 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 decreases the potential, leading to a possible overestimation of the results.

A detailed assessment of the cost-effectiveness of heat-saving measures 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 the gross and net savings approach, which translates in distinct levels of cost-effective measures according to building characteristics. Measures 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 [Figure 7](#), where we investigated on the average 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 the attrac-

tiveness.

Differently from other studies, the study assesses heterogeneous attractive heat-saving measures 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 measures, 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 measures among building categories, easing the development and design of policies, e.g. rebates or subsidies, for particular heat-saving measures.

For instance, analysing the outcomes in [Table 6](#), it results that most of the measures are cost-effective for buildings with low energy performance classes: on the total 50.35 GWh cost-effective gross savings, only 0.01 GWh are related to buildings with EPC A2020-A2015-A2010-B. Likewise for net saving potentials. Also, as the investments deemed worthy represent only a small fraction of the total potentials available, meaning that many other measures are yet to be attractive⁶, subsidies for heat-saving investments 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 measures are more attractive than others, policy support should be directed to the category with lowest investments. For instance, the results in [Figure 9](#), [Figure 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 seems 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 an heterogeneous approach can reveal attractive options, which would

⁶Compare the number of potential investments [Table 2](#) and the number of cost-effective investments [Table 6](#).

have been disguised with the use archetypes. Considering that Danish energy supply companies are required to realise heat-savings as long as cost-effective (Forsynings og Klimaministeriet, 2015; Forsynings og Klimaministeriet, 2018), the approach can surely supply more specific indications on attractive options.

The sensitivity analysis performed on input parameters 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 attractive savings. 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 pay-back periods, allowing a faster recover of investments, differently for each heat-saving measures. Lower discount rate can be related with lower taxation rates on loans from banks or other institutions; thus, local authorities in Aarhus, aiming at fostering the uptake of heat-saving interventions 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 structure. The sensitivity analysis shows that when all the cost components are made variable, the related investments in heat-saving measures distribute un-evenly among building categories based on the energy performance certificates (EPC) (See Figure 14). For buildings with high EPCs, most of the investments happens 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, building with low energy performances would not find

relevant an hypothetical disconnection, but they would benefit from a tariff that rewards the investments in savings.

Although advantageous from an investor perspective, such hypothetical heat-tariff structure can arise implications at energy system scale for the district heating (DH) companies. A reduction in the capacity costs can have negative implications for the district heating (DH) company, which has based its asset and investments on a plan of cost recovery. Hence, a decrease of 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. Indeed, if the overall demand of the building stock decreases and the savings 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 heat-saving measures 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 heat-savings 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 options and, in turn, heat-savings.

6. Conclusion and policy implications

In Europe, the residential building stock holds a large heat-saving potential related to energy-upgrading of the building envelope. Energy efficiency in build-

ings is expected to play a key role in future energy scenarios, reducing energy consumption and emissions. This study designs methods to analyse costs and saving potentials for heterogeneous building-tailored heat-saving measures and evaluate their cost-effectiveness. Based on a large buildings 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 heat-saving measures, using actual building characteristics and not synthetic archetypes, which are often employed for assessing saving 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) energy saving potentials, allowing a more accurate analysis of attractive heat-saving measures.

The study analyses attractive heat-saving measures based on net present value of cash flows, comparing investments with the cost of heat consumption over the 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, attractive gross and net saving potentials 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 of considering rebound effects (i.e. distinguishing technical and realistic potentials) and the modelling of building-tailored measures, rather than using archetypes. The outcomes show that cost-effective measures 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 measures distributed unevenly among building EPCs categories. The cost components provide different incentives to invest, according to EPC building categories. If investments in heat-savings can reduce the required capacity in district heating grids (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 heat-saving measures with energy systems analysis, to investigate the energy system impact of changes in heat-demand. In relation to this, the work should also focus on future projections of district heating costs.

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