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ORIGINAL ARTICLE

Energy efficiency inside out—what impact does energy efficiency have on indoor climate and district heating?

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Abstract This research study analyses the relationships between energy supply, energy-efficiency measures and indoor environment. Heat load duration profiles were applied for the purpose of analysing the quantitative impact on district heating production of energy-efficiency measures implemented in the multifamily housing stock of three Swedish municipalities. Further information on interconnections between energy efficiency, indoor environment and district heating was provided by qualitative assessments and stakeholder interviews. The intuitive conclusion is that energy savings captured during the winter season are more attractive to energy utilities. This is often, but not always true. The impact from energy savings will differ based on the heat production profile and the ratio between electricity and heat production in combined heat and power plants. Interviews suggest that residents only occasionally are involved, and energy companies are rarely consulted when property owners are implementing energy-efficiency strategies in multifamily residential buildings. This implies inadequate understanding of the implications to indoor environment and district heating production. Improvements in energy efficiency that go beyond cuts in peak load demand generally imply losses in profitability for energy utilities. There is thus little economic incentive for utilities to help their customers to implement energy-efficiency measures. Most often, energy utilities try to provide incentives through the design of heating prices, but pricing models are often complex and can be too difficult for property owners to understand. In order to achieve energy efficiency in a manner which is favourable for several parties, increased cooperation will be necessary.

Keywords Heat load duration · District heating · GHG emissions · Indoor environment · Energy-efficiency measures · Multifamily residential buildings · Linkages between energy utilities, property owners and residents

Introduction

Energy efficiency is high on the political agenda in Sweden, as in many countries, due to its positive effects

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on the environment, economy and society. Major focus is on energy efficiency in buildings, since they stand for a large share of the national energy consumption. The national energy-efficiency target is to reduce the building stock's energy consumption by 20% by 2020 (in comparison to 1995). According to the parliamentary Energy Agreement decided on in 2016, the target until 2030 is to improve the overall energy intensity by 50% (in comparison to 2005). Currently, a sector strategy for buildings is under preparation (Government 2017). Large-scale energy-efficiency improvements will have implications for both the energy and the housing sectors.

Several studies show that the cost-effective energy-efficiency potential in the Swedish building sector is significantly exceeding currently realised energy-efficiency actions (Persson and Göransson 2016, SKL 2011, Profu 2010, SOU 2008:110). Split incentives are an important explanation, for this energy-efficiency gap, the decision makers and beneficiaries are not necessarily the same actors (see e.g. Gerarden et al. 2015, IEA 2007, Maruejols and Young 2011). One such case is that property owners of multifamily residential housing restrain from investments because benefits of their investments accrue to the tenants. This happens even though residents are willing to pay higher rents for improvements in energy performance (Banfi et al. 2008, Phillips 2012). In another stream of literature, authors have studied the implications of energy-efficiency measures on the operation of the district heating system (Delmastro et al. 2017, Lundström and Wallin 2016, Difs et al. 2010).

The new aspect explored in this article is the expanded perspective viewing the effects at both ends of large-scale implementation of energy-efficiency measures. The linkages between energy supply, energy-efficiency measures and indoor environment are complex, and knowledge on these relationships is limited. To the authors' knowledge, previous research concerns the relationship either between energy-efficiency measures and energy supply or between energy-efficiency measures and indoor environments. The purpose of this research study was to apply a multidisciplinary approach for studying the relationships in the whole chain between energy supply, energy-efficiency measures and indoor environment (Fig. 1). Three questions were central for the study: "What are the synergies and conflicts of interests between indoor environment, energy efficiency and district heating?", "What is the role of property owners when implementing energy-efficiency measures?" and "What is the role of energy utilities and their pricing models?"

To answer these questions, the research involved case studies of three Swedish municipalities Östersund, Uppsala and Helsingborg. The municipalities are mid-size with 60,000–200,000 inhabitants, with district heating as the dominating choice of heating supply in multifamily residential buildings. In addition, a significant part of the housing stock in these municipalities was constructed between 1965 and 1975, and these buildings are currently in need of renovation. In order to learn more from past experiences of energy-efficiency projects, interviews were conducted with representatives of property owners of multifamily residential buildings. The interviews included questions on the choice of energy-efficiency measures, impacts on energy demand, consequences for indoor environments and stakeholder involvement.

The quantitative analysis of the case studies was based on Sweden's energy-efficiency target for multifamily residential buildings 2020. The analysis assumed theoretical combinations of energy-efficiency measures that would have significantly different impacts on the district heating production. As the basis for the calculations, energy production data for 2015 were provided by the district heating utilities from the three case study municipalities.

The next section describes the framework of analysis. After that, the following section introduces the case study municipalities and their district heating systems. Section 4 presents the results on the district heating systems and the environment from achieving the energy-efficiency target for buildings. Section 5 introduces a package of energy-efficiency measures, which in combination will achieve the target in the case study municipalities. After that, the impacts are presented concerning indoor environments and the district heating system. In order to analyse the role of the property owners, the profitability of the package and findings from interviews is presented. Section 6 summarises how the relationships manifest themselves in the chain between energy supply, energy efficiency and indoor

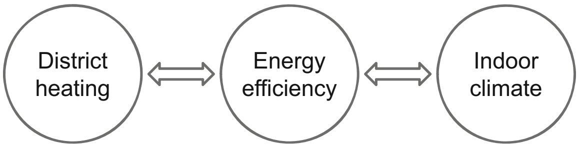

Fig. 1 Connections throughout the chain analysed in the study

environments. The last section concludes the research and discusses the roles of property owners and energy utilities.

The framework of analysis

Theoretical and empirical model of a district heating system

The impact on the district heating systems from energy-efficiency measures was assessed using data on heat load duration profiles. The duration diagram represents the annual heat load organised in a falling order from the peak hour to the lowest production period. The vertical axis represents the capacity requirement in a system in MW, and the horizontal axis shows the specific load's duration of time. In a load duration diagram, the different heat supply sources can be included based on minimum and maximum capacities, see Fig. 2. Data on heat load duration was applied to analyse how a change in total heat demand affects district heating production.

Energy-efficiency measures result in a lower heating demand, which in turn influences supply and reduces capacity requirement. The changes in demand that follow from the energy-efficiency improvements can be evenly distributed throughout the year, or they can be skewed towards energy savings during the summer or winter seasons, see Fig. 3. Measures with larger impacts during winter than summer time mainly concern climate shell improvements. Measures influencing domestic hot water supply in multifamily buildings result in an evenly distributed reduction of annual heating demand. Finally, installation of solar panels is an example of a measure that reduces district heating demand during summer time.

The empirical analyses rely on data of the combined heating and power generation or the district heating supply of each case study system in 2015. Based on hourly data and output associated with each boiler, simulation models were created for each case study system. Electricity generation fuels were allocated on the basis of co-generation. The simulation models allowed for evaluation of the impact from the energy-efficiency measures on the energy system. The analyses evaluated the impact of the quantitative 2020 target for energy efficiency. Simulations were made on the three different distributions of energy savings shown in Fig. 3. In order to investigate the determinants of the choice of investments in energy-efficiency measures and whether energy utilities are consulted prior to investments, interviews were carried out with property owners at the case study locations.

Appraisal of impacts on indoor environments

A search of literature to locate quantifiable cause-effect relationships between energy-efficiency measures and non-energy benefits on indoor environments suggested that results presented in the literature are too general for the purpose of this research. In one informative meta-study of energy-efficiency measures, the authors included more than 30 studies (Maidment et al., 2013). On a general level, they found that energy-efficiency improvements lead to a small but significant improvement of the health of the residents. However, besides additional insulation and high-performance windows, few additional measurs were included. In some of the studies, observations of positive health effects from energy-efficiency improvements are associated with counter measures to relief of sick-house syndrome (see e.g. Liu and Thoresson 2013) or addressing fuel poverty

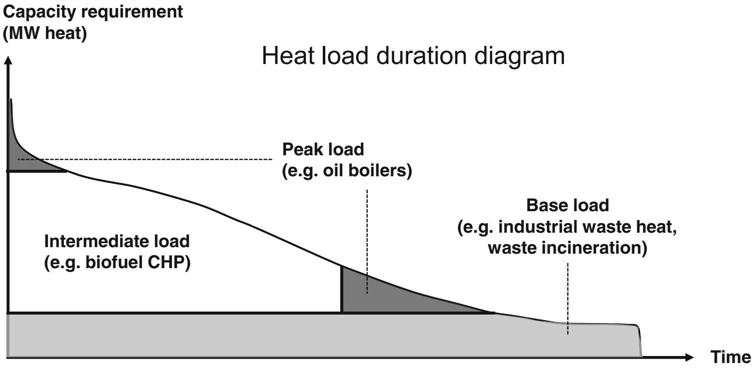

Fig. 2 Heat load duration diagram of a typical district heating system with base, intermediate and peak load boilers

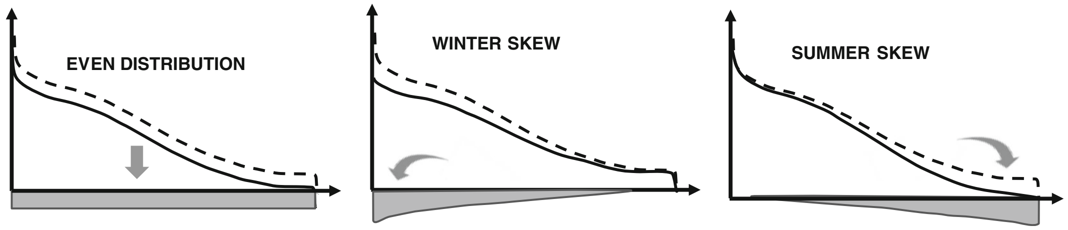

Fig. 3 Theoretical outcomes of reductions in heating demand on district heating

(IEA 2014), suggesting that these results relate to specific conditions not to the general case. For these reasons, qualitative expert appraisals were applied.

The aim of the expert appraisals was to assess the general cause-effect relationship from energy-efficiency measures on indoor quality. The impact on the indoor indicator will depend on the baseline conditions of the building, which creates a challenge for basing the analysis on general effects. Moreover, energy-efficiency measures were assumed to be carried out in a professional manner. In a first step, the research team appraised 11 energy-efficiency measures qualitatively. The assessment concerned expert judgements about how specific indoor air quality indicators would be affected by the measure in question. As a support to expert appraisals, literature on energy-efficiency improvement measures in multifamily buildings and building-type calculations provided guidance. Important input was gathered from the Swedish Energy Agency supported networks BeBo (n.d.) and BeLok (n.d.)[1] and a research project called HEFTIG carried out on behalf of the Energy Agency (CIT et al. 2016). In a second step, the results of the initial assessment were presented to the reference group. The assessments were discussed and revised.

The impact of energy-efficiency measures on indoor environment quality was assessed based on the Swedish sustainability certification system, "Miljöbyggnad 2.2", launched by the Sweden Green Building Council (2014). This certification system was chosen for the purpose of analysis as it is used widely within the Swedish property sector. Miljöbyggnad 2.2 includes a set of nine quality indicators, which characterise different aspects of the indoor environment quality, see Table 1.

The impact of the energy-efficiency measures on indoor environment quality was assessed qualitatively by using a four-level scale (−, 0, +, ++). While carrying out the expert appraisals, some adjustments were made. The initial five-point scale (−−, −, 0, +, ++) was abandoned, since it proved to be difficult to make a distinction between large negative and small negative impacts. Additionally, the nitrogen dioxide indicator was omitted in the analysis since no clear cause-effect relationship between energy-efficiency measures and indoor environment quality was found. One reason for this is that residential buildings generally are located at some distance from the district heating plants in Sweden.

Case studies

Table 1 Indoor environment indicators. Source: Sweden Green Building Council (2014)

Indicator	Description
Indoor acoustics	Indicator to ensure favourable indoor acoustics
Radon	Indicator to ensure low levels of radon
Ventilation	Indicator to ensure favourable ventilation
Humidity control	Indicator to ensure that no moisture problems occur
Legionella	Indicator to ensure that no problems occur with legionella
Thermal indoor climate wintertime (winter)	Indicator to ensure a favourable thermal indoor climate wintertime
Thermal indoor climate summertime (summer)	Indicator to ensure a favourable thermal indoor climate summertime
Daylight	Indicator to ensure favourable level of daylight
Nitrogen dioxides	Indicator to ensure low levels of nitrogen dioxides in the building

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[1] The Swedish networks BeBo (multifamily property owners) and BeLok (commercial property owners) aim at reducing energy demand and environmental impacts from the built environment. They carry out energy-efficiency development projects, provide exchange of information and experiences on energy-efficiency projects and have produced calculation methods and general recommendations for energy efficiency renovations.

Three Swedish municipalities with different climate conditions were selected as case studies. Östersund is located in the north of Sweden, Uppsala is geographically located in the middle of Sweden and Helsingborg in the south. During the coldest month of the year (February), the average temperature is − 9 °C in Östersund, − 4 °C in Uppsala and 0 °C in Helsingborg (SMHI n.d.). In terms of population, the case studies are mid-sized. Table 2 provides facts on the population in the case study municipalities, total district heating supply and district heating supply to multifamily houses in 2015 and the number of flats.

In the northernmost case study municipality Östersund, the district heating system, owned by Jämtkraft AB, delivers district heating to Östersund municipality and to neighbouring town Krokom. The district heating system of Uppsala is owned by Vattenfall Värme AB. In addition to Uppsala, Vattenfall Värme supplies the neighbouring town Knivsta with district heating. Finally, the district heating system of Helsingborg covers the municipalities Helsingborg and Ängelholm and parts of Landskrona municipality. Its owner Öresundskraft AB has recently connected the district heating system to that of Kraftringen AB, making it possible to exchange heating through a joint pipeline system. The market share of district heating sales to multifamily residential buildings is approximately 50% in the case studies. It is expected that multifamily residential buildings built in the 1960s and 1970s are in a major need of retrofitting and will be subject to major energy-efficiency measures. Generally, major renovations occur every 40th to 50th year. In the three case study municipalities, 34–43% of the multifamily housing stock were built during this time period. Previous studies have shown that only 17% of the multifamily buildings built in 1961–1970 and 11% of those built in 1971–1980 have already been renovated (CIT, WSP and Profu 2016).

The three case studies differ to some degree concerning fuel use in the district heating system. The district heating system in Östersund is almost entirely biomass based. The oil-fired peak boiler is used primarily during cold winter days. In the case of Uppsala, heat recovery from waste incineration constitutes the base load of the city's district heating system. The base load in the district heating system in Helsingborg is a combination of household waste incineration and industrial waste heat. All three district heating systems in this analysis rely to some degree on co-generation of electricity and heat in combined heat and power (CHP) plants, but the running scheme differs between them, see Table 3.

The district heating system in Östersund includes a biomass-fired CHP plant at Lugnvik, which provides the system's main capacity of 110 MW heat (of which 30 MW from flue gas condensation) and three smaller boilers, each with a capacity of 25 MW. In periods with low heating demand, energy is provided from the smaller boilers. When capacity requirement increases, production shifts to the CHP plant. For the coldest periods with peak demand, Jämtkraft's peak load capacity is based on oil.

In Uppsala, the district heating system base load is generated by energy recovery from waste incineration. This is supplied from Uppsala Block 5, a plant with a heat capacity of 75 MW. Peat and biomass currently make up the intermediate load fuels, partly fired in a CHP plant. Heat pumps support the intermediate load boilers. A new plant is under construction and will substitute the system's remaining peat with biomass. The Uppsala peak load is based on electricity and oil.

The base load of the district heating system in Helsingborg is a combination of industrial waste heat and household waste incineration. The waste incineration plant at Filborna co-generates heat and electricity, with a heat capacity of 60 MW. A biomass-fired CHP plant

Table 2 Case study municipalities (2015)

Owner of district heating system	Municipalities	Population	Distict heating delivery, GWh	Apartments in multifamily housing	
				Total	Constructed in 1961–1980
Jämtkraft AB	Östersund/Krokom	75,800	600	20,900	9000 (43%)
Vattenfall Värme AB	Uppsala/Knivsta	227,000	1589	61,400	20,600 (34%)
Öresundskraft AB	Helsingborg/Ängelholm	179,000	1100	48,900	18,000 (37%)

Table 3 Case study district heating systems (2015)

		Fuel	Boiler
Östersund	Base load	Biomass	Heat boilers
	Intermediate load	Biomass	Co-generation
	Peak load	Oil	Heat boilers
Uppsala	Base load	Waste incineration	Heat boilers
	Intermediate load	Electricity	Heat pumps
	Intermediate load	Peat/biomass	Co-generation
	Intermediate load	Peat/biomass	Heat boiler
	Peak load	Electricity and oil	Heat boiler
Helsingborg	Base load	Industrial waste heat	Process heat
	Base load	Waste incineration	Co-generation
	Intermediate load	Biomass	Co-generation
	Intermediate load	Electricity	Heat pumps
	Peak load	Natural gas	Heat boiler

and heat pumps account for the intermediate load, and the peak load is generated in a natural gas boiler.

Impacts on the district heating systems

The analysis of the impacts on district heating systems was based on the Swedish energy-efficiency quantitative 2020 target. It requires the energy demand per heated floor area to be reduced by 20% in comparison to the reference year 1995.[2] Calculations based on national data for 2015 in comparison to 1995 showed that approximately 9% remains to be achieved if the goal is to be met (Swedish Energy Agency 2016). These 9% energy savings were assumed to be achieved by energy-efficiency measures leading to the corresponding decline in heat supply in the three case studies' district heating systems.

Energy savings

Three different analyses were carried out in each case study. The first calculation assumed that the reduction in demand was evenly distributed throughout the year. The second assumed that the energy savings were skewed towards a larger reduction during the winter time, and the third calculation assumed that savings primarily were achieved during the summer season. The results are presented in Table 4, as decline in heat supply per fuel source.

The impacts of energy-efficiency measures vary depending on the production profile of the district heating system, i.e. boiler capacities, load order of the boilers and types of fuels consumed in the systems. All three of the studied district heating systems rely to a certain degree of co-generation of electricity and heat in CHP plants. Seasonality of electricity generation varies between case studies. Uppsala generates electricity during the four coldest months of the years, while Helsingborg has year-round coverage of CHP. Östersund has CHP coverage during approximately nine months.

In Östersund, the energy savings goal of 9% corresponds to a reduction of 52 GWh district heating per year. Since the oil-fired peak boiler is used primarily during the winter, the impact on the peak production in Östersund would be largest in the case of winter skewed energy savings. This would be positive both from an environmental and a financial perspective. There would be less need for fossil fuels (used during peak production periods), and the savings would occur during the period when expensive fuels are used in peak production. At the same time, however, the use of Jämtkraft's CHP capacity would decrease. This would lead to a reduction in electricity generation.

In Uppsala, the simulated energy savings correspond to a reduction of 143 GWh heat supplied in 2020. The use of the peak boiler would decline significantly with winter

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[2] Governmental proposition 2005/06:145. Definition of floor area excludes e.g. stair well and basement from overall floor area, while electricity for operation of the buildings and energy for hot water production are included, see Energy indicators 2016, Swedish Energy Agency, 2017.

Table 4 Decline in district heating supply at 9% of energy savings, GWh per annum

	Boiler and fuel	Even distribution	Winter skewed	Summer skewed
Östersund	Biomass, heat boiler	18.3	12.6	23.9
	Biomass (CHP)[a]	42.8	50.0	35.9
	Peak boiler (oil)	1.6	1.9	1.1
	District heating saving, total	**52.0**	**52.0**	**52.0**
	Loss of electricity production	**10.7**	**12.5**	**9.0**
Uppsala	Waste incineration, heat boiler	52.5	6.1	73.5
	Heat pumps	9.4	3.8	13.0
	Peat/biomass (CHP)[a]	49.8	97.2	20.9
	Peat/biomass, heat boiler	47.1	65.7	42.6
	Peak boiler (oil, electricity)	1.0	3.0	0.0
	District heating saving, total	**143.0**	**143.0**	**143.0**
	Loss of electricity production	**16.8**	**32.9**	**7.1**
Helsingborg	Industrial heat	0.4	0.0	4.0
	Waste (CHP)[a]	51.9	14.2	79.1
	Biomass (CHP)[a]	31.5	66.7	10.4
	Net imports (bio + waste)	15.3	11.7	14.3
	Heat pumps	17.1	26.2	7.9
	Peak (natural gas)	0.3	0.7	0.1
	District heating saving, total	**94.0**	**94.0**	**94.0**
	Loss of electricity production	**22.5**	**25.5**	**21.7**

[a] Fuel use in combined heat and power plants (CHP) include fuel for electricity generation. Hence, the district heating does not sum in total

skewed savings, while the impact on peak load is negligible for summer skewed savings. Furthermore, the implications for Vattenfall's base load waste incineration vary significantly between the winter and summer cases. Waste incineration would decline considerably when assuming evenly distributed or summer skewed savings, while a winter skewed energy savings distribution would have very little effect on the base load. The difference between winter and summer skewed energy savings would be approximately 70 GWh heat from waste incineration in 2020. In addition, the loss of electricity production would be approximately 25 GWh larger in the case of winter skewed savings compared to the summer skewed savings. The environmental impact of the loss in electricity generation depends on how the lost co-generated electricity would be replaced.

In Helsingborg, the 2020 goal of 9% reduction would imply savings corresponding to 94 GWh heat in the district heating system. The impact on peak production would not be as significant in Helsingborg as in the other two case studies. Likewise, the effect on loss of electricity supply of different saving profiles would be relatively small in Helsingborg, since Öresundskraft's two CHP plants cover different periods in the heat load duration diagram.

Environmental effects

The decrease in fuel consumption has positive implications on greenhouse gas emissions and on primary energy demand. In order to find the order of magnitude, carbon dioxide emission and primary energy factors agreed on by the members of the Swedish Heating Market Committee were applied (Swedish Heating Market Committee 2015; see also Swedish District Heating Association 2016).[3]

The three case studies show different patterns in reduction of greenhouse gas emissions. In Östersund and Uppsala, winter skewed energy savings would contribute to larger reductions in greenhouse gas emissions than summer skewed or evenly spread energy savings, see Table 5. This result is particularly clear in Uppsala. In Helsingborg, summer

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[3] The emission factors and the primary energy factors are based on life cycle assessments, including energy conversion in the heat plant, production and transportation of fuels.

Table 5 Assessment of greenhouse gas emission reductions from energy savings with respect to seasonality

		Even distribution	Winter skewed	Summer skewed
Reduction of $CO_{2\text{-e}}$ emissions, (tons $CO_{2\text{-e}}$) (electricity excluded)	Östersund	1440	1560	1290
	Uppsala	28,400	38,500	23,200
	Helsingborg	8800	6600	10,000
Critical emission factor of $CO_{2\text{-e}}$ (kg/MWh replacement electricity)	Östersund	$65 < x < 89$	$0 < x < 65$	$x > 89$
	Uppsala	–	$0 < x594$	$x > 594$
	Helsingborg	–	–	$x > 0$

skewed savings would lead to the most significant CO_{2e} reductions. The assumption is that fuel supply can be altered in proportion to savings. Since Helsingborg relies on waste incineration as a base load, summertime savings could imply that waste has to be incinerated without heat recovery. The reason is that waste is a fuel that cannot be stored. Thus suggesting that the environmental effect of summertime savings could be overestimated.

Another important factor to consider is the trade-off between emission reductions caused by lower heat demand on the one hand, and the loss of electricity generation on the other. It was previously found that the largest loss of electricity production would occur with winter skewed savings. This result is significant for Uppsala but less obvious for the two other cases. The outcome of this trade-off will depend on the assumptions on how the lost electricity production will be replaced. In order to specify the limits, emission factor intervals were calculated for replacement electricity, see Table 5.

In Östersund, winter skewed savings perform the best from a CO_{2e} perspective. When accounting for reduced electricity generation, the outcome of Östersund changes if the emission factor of the replacement electricity exceeds 65 kg CO_{2e} per MWh. An emission factor between 65 and 89 kg CO_{2e} per produced MWh electricity results in evenly distributed energy savings providing the best environmental performance for Östersund. For emission factors above 89 kg CO_2 per MWh electricity, energy savings during the summer season have the best environmental performance. As a comparison, the emission factor of the Nordic residual electricity mix was 336 kg CO_{2e} per MWh in 2015.[4] This suggests that summer skewed savings would be rated as the best if the replacement electricity would be based on the Nordic residual mix. Admittedly, this is a simplifying assumption since this interpretation does not take into account that the production mix of electricity also varies by season. Reduced electricity generation during the winter period is likely to have a larger impact in the Nordic electricity system, as electricity peak demand normally occurs during the cold season. In Uppsala, the winter skewed energy savings would bring about superior environmental performance as long as the emission factor of the replacement electricity would be below 594 kg CO_2 per MWh. Hence, winter skewed savings would be best for Uppsala from an environmental perspective.

Helsingborg differs from the other two case studies by achieving the highest greenhouse gas emission cuts with summer skewed energy savings. Since the loss of electricity production would be lowest when savings occur in the summer season, the emission factor of replacement energy would have no influence on the environmental performance.

The demand for primary energy resources is another way to describe the environmental effects of the savings. Primary energy measures the resource use, i.e. the necessary quantity of energy resources for producing the heat required to satisfy demand. Fossil fuels and primary biofuels require higher levels of primary energy than waste and secondary biofuels. In the three case studies, heat is mainly generated from waste and secondary biomass, implying that the savings of primary energy use are considerably smaller than savings in energy demand. Significant differences can be seen between the three studied district heating systems, see Table 6.

In Östersund, the three seasonal distributions are similar in terms of primary energy demand. The

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[4] http://www.ei.se/sv/for-energiforetag/el/ursprungsmarkning-av-el/ accessed 13.01.2017. As a comparison, electricity generated in gas combined cycle condensing power with efficiency of 58% has an emission factor of 370 kg CO_2/MWh (see Difs et al. (2010)).

reduction of fossil oil explains why the evenly distributed and winter skewed savings would be slightly higher than the savings in the summer season. Uppsala and Helsingborg show significant seasonal variations in primary energy demand. Winter skewed savings would have a high primary energy factor, which would result in the best outcome concerning resource use. The relatively low impact on primary energy demand when savings are summer skewed is due to the fact that summer savings primarily concern waste heat, which has a low primary energy factor. The combination of industrial waste heat and waste incineration as in Öresundskraft's fuel mix brings about a higher relative difference between the winter skewed and summer skewed savings profile in Helsingborg in comparison to Uppsala, which relies on waste incineration.

Conclusions—energy supply

An intuitive conclusion is that energy savings achieved during the winter season are more attractive, as they lead to a more even district heating production over the year. This conclusion is often, but not always, valid. The subsequent losses in electricity production in CHP plants that follow from reduced heating demand also have an impact on the results. The environmental outcome depends on how the lost electricity production will be replaced. Furthermore, the three case studies show that district heating systems based on biomass, resembling that of Östersund's, are affected differently by energy-efficiency measures than district heating systems where industrial waste heat and/or waste incineration serve as base load.

In order to generalise the conclusions drawn from the case studies, two hypothetical heat load duration diagrams for district heating systems are illustrated. One of them is appropriate to winter skewed energy savings and the other appropriate to summer skewed energy savings, see Fig. 4.

Table 6 Savings in heat energy and primary energy (electricity excluded), GWh per annum

	Savings of delivered district heating	Primary energy savings		
		Even distribution	Winter skewed	Summer skewed
Östersund	52	4	4	3
Uppsala	143	61	91	46
Helsingborg	94	47	72	24

Both systems are assumed to have peak load oil boiler capacity for cold winter days. In the system appropriate for winter skewed energy savings, waste incineration in a co-generation plant provides base load heat and electricity. Since waste is a fuel that cannot be stored, this system would run and secure electricity generation throughout the year. Waste is also a fuel with negative costs, i.e. the energy utility is paid by the waste supplier for taking care of the waste, and it makes economic sense for the utility to run the waste incinerator even during periods when there is low or no demand for the produced heat. Intermediate load is supplied from a biomass-fired CHP plant.

The district heating system appropriate to summer skewed energy savings uses a large biomass-based CHP as its main heat source during the colder part of the year. This CHP is assumed to have a minimum load capacity, under which it cannot run. Below this CHP minimum load level, a biomass-based heat boiler provides the heat to the system. The minimum capacity of the CHP plant limits the period when electricity production will be lost as a result of summer skewed energy-efficiency measures. Hence, reducing the heat demand in summer will only result in a negligible reduction in electricity generation. Winter skewed energy-efficiency measures will, on the other hand, cause significant losses in electricity production, as the CHP provides most of the heat during the cold winter period.

Energy-efficiency measures

The analysis of energy-efficiency measures was based on the quantitative Swedish energy efficiency 2020 target. In a first step, the relevant multifamily housing stock of the case study municipalities was identified and a package of energy-efficiency measures was selected. The performance of the package of measures was then assessed concerning its impact on the indoor environment quality and on the district heating system. In order to analyse the role of the property owners, the profitability of the package was calculated and the implementation of energy-efficiency measures was discussed in interviews with property owners.

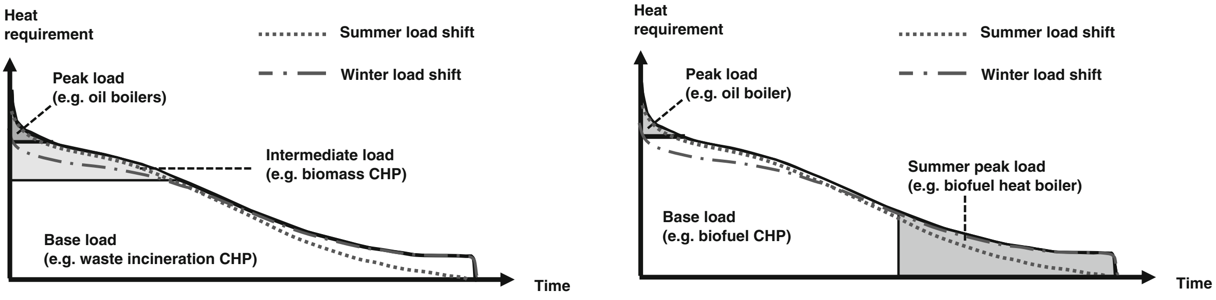

Fig. 4 A district heating system design appropriate for winter skewed energy savings (left) and a district heating system design appropriate for summer skewed energy savings (right)

Housing stock in need of renovation

When defining the 2020 energy-efficiency goal for multifamily residential buildings, it seems reasonable to assume that the 9% savings level for multifamily residential buildings should be based on their share of district heating supply, see Table 7. Major energy-efficiency measures are often implemented in multifamily residential buildings when the buildings are undergoing significant renovations. In order to define the relevant housing stock in the three case studies, the number of apartments in need of renovation was calculated based on those constructed during the time period 1961–1980 (see Table 2). From this number, those already renovated were subtracted. The remaining number was defined as the potential for energy-efficiency improvements in these buildings, i.e. apartments in buildings in need of renovation.

Based on the target, the savings level assigned to multifamily buildings would be approximately 27 GWh in Östersund by 2020. These savings are attributed to approximately 7200 flats in need of renovation in Östersund and the neighbouring municipality Krokom, which is supplied with district heating from the same system as Östersund. Without additional energy-efficiency measures, it was assumed that the average energy demand per apartment is approximately 10,000 kWh per year,[5] implying that current aggregated energy demand is approximately 72 GWh per annum. Energy-efficiency measures that reduce the energy demand by 40% would be necessary in order to reach assigned savings level. The results for Uppsala and Helsingborg are similar.

Impacts on indoor environments

Energy-efficiency measures implemented in standard houses from the 1960s and 1970s were studied in a report to the Swedish Energy Agency (CIT et al. 2016). Two packages of energy-efficiency measures were designed for multifamily buildings: one with measures that would improve the energy performance of an individual building by 30% and another that would improve the energy performance by 50%.

In order to meet the 2020 goal in the three case study municipalities, it will be necessary to implement more stringent packages of energy-efficiency measures than the one leading to 30% energy savings. For this reason, the 50% package is the starting point of the evaluation of the impacts on indoor environments. This package includes eleven energy-efficiency measures, shown in Table 8.

The eleven measures were appraised according to their impact on indoor environment quality (based on the Swedish environmental certification system Miljöbyggnad 2.2) and whether they lead to an evenly distributed or a seasonal energy-efficiency improvement signature. The results of the appraisals suggested that most impacts on the indoor environment quality would be positive. In addition to improving indoor thermal comfort wintertime, measures for improved insulation of the building envelope and window replacements affect indoor acoustics by reducing noise levels. The energy-efficiency measures would only have few potential negative impacts, including less daylight from energy-efficient windows and more indoor noise from improved mechanical ventilation systems. This led to the overall conclusion that the package implies a

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[5] Data from the annual housing survey of Statistics Sweden were consulted for the case study municipalities, but data did not imply there are any significant differences in energy use depending on location in Sweden. Source: Statistics Sweden 2016, Energy use per square meter in residential buildings by type and period of construction.

Table 7 Assignment of savings levels to 2020 to multifamily housing in need of renovation

	Östersund/Krokom	Uppsala/Knivsta	Helsingborg/Ängelholm
Delivery, district heating to multifamily housing, GWh/year	294	747	605
Target savings level for multifamily housing, GWh/year	27	67	55
Total number of apartments built in 1961–1980	9000	20,600	18,000
Apartments in buildings in need of renovation	7200	16,900	15,300
Total energy demand, GWh/year	72	169	153
Energy savings 25%, GWh/year	18	42	38
Energy savings 40%, GWh/year	29	68	61

positive impact on indoor environment quality. Another implication is that measures for improved climate shell performance, improved mechanical ventilation and improved heating distribution control measures have the best potential to improve the indoor environment in a cold climate.

A majority of the energy saving measures in the 50% package were assessed to have a larger impact at cold weather conditions, thus causing a winter skewed reduction of the district heating demand. The energy savings would cut peak fuel use, but also lead to a loss in electricity generation. This would be the outcome in all three case studies, but most obvious in the district heating system of Uppsala. From an environmental point of view, the loss of electricity in Uppsala could be substituted by Nordic residual mix, without trading off the CO_2 reduction from lower use of fuel for heating. However, in Östersund, this is not the case. Substituting the lost electricity with Nordic residual mix would lead to a net increase in CO_2 emissions.

Financial profitability

In order to decide on financial profitability of the 50% package, life-cycle costing (LCC) was applied. The life-cycle approach includes costs during a long time period. For this purpose, discounting was needed for future costs and revenues. Financial profitability was based on the net present value (NPV) of the energy savings throughout the lifetime of the measures in comparison with the initial capital cost, see below equation.

$$NPV = \sum_{t}^{T} \frac{C_t}{(1+r)^t} - CC_0$$

where CC_0 stands for the initial capital cost, i.e. the investment. Since it is assumed that investments in energy-efficiency improvements are implemented as a part of building renovation works, CC_0 accounts for the investment cost in addition to standard renovation (see Pädam et al. 2016). Annual energy savings multiplied by energy prices (taxes included) is denoted by C_t, and r stands for the interest rate. Energy savings are discounted with the social interest rate of 4%. This level of social interest rate is recommended by the EU Commission (European Commission Better Regulation n.d.). The evaluation period is based on the expected lifetime of the new building components. In correspondence with assumptions made by the Swedish Energy Agency, the lifetime is 40 years of building envelope measures and 20 years of HVAC installations.[6] Energy prices (taxes included) were assumed to be SEK 0.89 per kWh (EUR cent 9.4/kWh) for heat and at SEK 1.46/kWh (EUR cent 15.4/kWh) for electricity (Pädam et al. 2016). The net present value was determined for fixed energy prices and for increasing energy prices. Assuming energy prices increase at a rate of 1.25% annually, the profitability of the 50% package passes the break-even point.

The estimates suggest that profitability can be a problem for the package and for major energy-efficiency measures, including improved climate shell, window replacement and improved mechanical ventilation. High initial capital costs imply that market prices might not provide sufficient incentives to undertake these energy-efficiency measures.

Choice of measures in past projects

At the case study locations, interviews were conducted with representatives of property owners of multifamily residential buildings, including both owners of rental

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[6] Heating, ventilation and air conditioning (HVAC).

Table 8 Energy-efficiency measures, indoor environment, seasonal distribution and profitability

Energy-efficiency measure	Impact on indoor environments	Seasonal distribution	Share of savings of the 50% package	Profitability SEK/m^2	
				Fixed prices	Increasing prices, 1.25% p.a.
Improved climate shell (additional insulation)	Acoustics (++) Winter (++) Summer (+)	Winter skewed	12%	−310	−270
Improved attic insulation	Acoustics (+) Winter (+)	Winter skewed	7%	80	110
Window replacement (high-performance windows)	Acoustics (++) Winter (++) Summer (++) Daylight (−)	Winter skewed	6%	−220	−190
New front doors	Acoustics (+) Winter (+) Summer (+)	Winter skewed	5%	40	60
Individual metering and billing of domestic hot water	No impact on indoor climate	Even distribution	5%	0	10
High-performance tap water mixers	No impact on indoor climate	Even distribution	6%	50	60
Improved mechanical ventilation with supply and exhaust air and heat recovery	Acoustics (−) Radon (+) Ventilation (++) Winter (++) Summer (++)	Winter skewed	35%	−40	60
Heat load control thermostats	Winter (++) Summer (++)	Winter skewed	13%	80	90
LED lighting with occupancy sensors	No impact on indoor climate	Even distribution	1%	−3	−1
Balancing of ventilation system	Ventilation (+)	Winter skewed	5%	60	70
Heat recovery from domestic hot water	No impact on indoor climate	Winter skewed	5%	0	10
Sum			100%	−263	9

housing and representatives of housing co-operatives. The purpose was to discuss the role of the property owners and to further understand their reasoning when implementing energy-efficiency measures.

Interviewees suggested that energy-efficiency improvements generally are undertaken in buildings in need of renovation. High energy costs were also mentioned as a potential motive. There is, however, an important distinction between municipality-owned housing companies and private housing co-operatives in terms of knowledge and motivation. While municipality-owned housing companies have a professional management organisation and most often energy-efficiency or environmental performance targets, interest and experience in energy-efficiency improvements are low in private housing co-operatives. A mere 10–15% of the private housing co-operatives are interested in energy-efficiency performance according to one of the representatives of a housing co-operative management association.

In the interviews, the representatives of the municipality owned housing companies reported that energy-efficiency measures are generally not eligible for rent adjustments according to the national property rent legislation. In Sweden, rents are set in negotiations between the tenants' association and the property owner (or the property owners association). The base for negotiations is the utility value of the apartment. Rents are to a large degree based on "visible" factors including kitchen and bathroom equipment.[7] For this reason, the costs of energy-efficiency measures cannot easily be transferred to tenants. In housing co-operatives, on the other hand, there is a direct link between property management costs

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[7] The utility value includes aspects that relate to the standard and modernity of the apartment and its equipment.

and the monthly fee the residents pay to the co-operative. Information from interviews implies that residents in private housing co-operatives are sensitive to increases of the level of the fee. Since the fee has an impact on the selling price of an apartment, it is sometimes difficult to back up investment decisions on energy-efficiency improvements.

In discussions on the choice of measures, the interviewees found it difficult to point out how choices had been made when selecting energy-efficiency measures in past projects. One interviewee, representing a municipality-owned housing company, mentioned that designing the package of measures was the task of the engineering department. Another interviewee reported that their goal is to improve energy performance by 30%, but projects covering both building envelope measures and ventilation often perform better. At the same time, architectural design restrictions make up a possible obstacle for changes of the façade, implying some buildings have lower savings potential. Several interviewees brought up mechanical ventilation with heat recovery. As disadvantages, they mentioned high investment costs and potential problems to find enough space for supply air ducts in existing buildings. Advantages that were mentioned included significant contribution to energy performance and indoor environment quality improvements. It was also pointed out that these advantages are more pronounced in the north of Sweden than in the south. Several interviewees reported that improvements in heating energy performance had led to increased demand for electricity. The reason is that heat-recovery measures require additional fans and pumps. Making an attempt to conclude how past measures have affected the seasonal distribution suggests that energy savings most likely follow the winter skewed savings profile.

Linkages between district heating and indoor environment quality

Property owners are the key players in the chain between energy efficiency and energy supply on the one hand, and energy efficiency and indoor environment quality on the other hand. In order for property owners to make adequate choices of measures, they need to base their decisions on information on the energy performance and the quality of the indoor environment.

Discussions with property company representatives indicate that they hardly have any contacts with their energy suppliers prior to the property owners' investments in major energy-efficiency measures. They do not seem to consider energy suppliers as potential partners in energy-efficiency projects. Neither do the concerned energy utilities include energy-efficiency consultation in their business model. The case study energy utilities charge for heat according to a three-part tariff system. One fixed part, a second semi-fixed price based on previous heat consumption and a third seasonal per kWh price. Incentives provided by local heat prices have potential influence, but price information is not in systematic use. Lack of transparency of the price system is considered to be one reason for not making more use of pricing information. Other interviewees express dissatisfaction with the fact that adjustments of the semi-fixed capacity tariff are made one or even three years subsequent to the lower level of energy demand, implying there will be a time gap between implementation and reaping full cost savings from energy-efficiency measures. This dissatisfaction seems to be related to a low level of knowledge of price design and structure among property owners.

Interviews suggest a large variation in tenant involvement, from no involvement at all to extensive participation processes. One interviewee, representing a municipality-owned housing company with no tenant involvement, reports that they received fewer complaints after the implementation of the energy-efficiency improvements than prior to the renovations. Previously, many complaints concerned draught. Currently, there are no such complaints. However, no interviewee reports the use of surveys for detecting the difference in tenant level of satisfaction with indoor environments before and after the renovation. Neither were sustainability certification systems consulted when investments in energy-efficiency measures were decided on and implemented. Table 9 maps the interconnections between the various stakeholders by categorising them into monetary and non-monetary costs and benefits.

For energy utilities, winter skewed energy savings will be beneficial as long as lower demand cuts peak production in winter time. The savings in peak production costs will cover lower revenues. Moreover, the utilities' environmental performance improves when the use of peak load fossil fuels can be cut. Since the

Table 9 Linkages through monetary and non-monetary costs and benefits of energy-efficiency improvements

	Energy utilities	Property owners	Residents
Monetary costs	Lower revenues Production costs	Investment costs Capital costs Higher electricity costs	Adjustment of fee/rent Selling prices of co-op. apartments
Monetary benefits	Production costs	Lower heat costs Property value? Adjustment of fee/rent[a]	[a]
Non-monetary costs	Potential decrease in customer loyalty for slow adjustment of heat tariffs	Lack of knowledge; private housing co-operatives	
Non-monetary benefits	Customer satisfaction Environmental performance	Less complaints Environmental performance	Indoor environment quality

[a] Savings from lower heating and hot water bills are reaped by the property owners

environmental performance of the heating distribution is valued by certain property owners, this is a potential non-monetary benefit. However, energy utilities are rarely consulted when implementing energy-efficiency strategies and the limited understanding of the implications on the district heating production could influence the outcome adversely. The outcome could imply revenue losses exceeding savings from production costs. Three-part tariffs safeguard against short-time fluctuations, but this pricing system has a negative impact on customer loyalty, resulting in non-monetary costs.

From the energy utility perspective, successful implementation of combinations of energy-efficiency measures implies potential cuts in peak load capacity and resumed customer loyalty. In the traditional business model of utilities, where revenue comes from selling kWh of district heating to customers, improved large-scale implementation of energy-efficiency measures leads to losses for the heat provider. There is thus little economic incentive for utilities to help their customers to carry out energy-efficiency measures. If the customers are improving their energy performance, encouraged by environmental targets and potential economic benefits, the utilities risk to encounter other losses from not participating in the process. Utilities can take a more active role in ensuring that the implemented energy-efficiency measures have positive effects on their district heating production. This will require them to develop business models that can decouple revenues from sold kWh of heating and focus more on providing energy as a service.

Property owners commonly accept additional investment costs of energy-efficiency improvements when buildings are in need of renovation. However, the subsequent savings in energy costs might not balance potential capital costs. Residents benefit from improved indoor environment quality, but there is little influence on rents. It is possible though that better indoor air quality reach property owners in terms of a non-monetary benefit by means of fewer complaints and less relocations. In the long run, property owners expect a positive impact on property values, but empirical evidence between property prices and energy performance is weak (Sayce et al. 2010). In private housing co-operatives, there is a connection between the sales price of the apartments and the fee, but this suggests that lower levels of energy-efficiency improvements will be accepted since sale prices tend to decrease with higher fees.

Conclusions

Three questions have been central for this study. The first one was "What are the synergies and conflicts of interests between indoor environment, energy efficiency and district heating?" The analyses of the three district heating systems suggest that energy-efficiency measures in the Nordic climate most often lead to winter skewed energy savings and the implications on indoor environment quality are generally positive. As long as winter skewed energy savings only cut the winter peak demand, energy-efficiency improvements will benefit all stakeholders. However, energy-efficiency goals entail large-scale cuts in energy demand, which indicate adverse impacts on the economies of scale of district heating. Besides cuts in district heating demand, energy-efficiency measures have implications on the supply and demand for electricity. Firstly, significant winter skewed energy savings imply a loss in electricity production, and secondly, several energy-efficiency measures increase the electricity demand.

The second question was “What is the role of property owners when implementing energy-efficiency measures?” Interviews with owners of multifamily buildings confirm that the implementation of energy-efficiency measures most often is based on renovation needs. Although some communication exists between property owners and energy utilities, there is generally no involvement of the utility when the property owners are deciding on and implementing energy-efficiency strategies and measures. Neither is there a systematic involvement of tenants nor are sustainability certification systems systematically consulted. The implication of tenants only being occasionally involved is that the energy-efficiency measures’ added value to indoor environment is invisible to the property owners. For these reasons, there is a risk that property owners choose non-optimal sets of energy-efficiency measures. Another concern is that current energy-efficiency incentives are too weak to meet the 2020 energy target for multifamily buildings.

Discussions with representatives of district heat suppliers and property owners provided input to the third question “What is the role of energy utilities and their pricing models?” These discussions suggest that the traditional business model of energy utilities is to earn revenues from selling kWh. Improvements in energy efficiency that go beyond cuts in peak load demand generally imply losses in profitability for the energy utilities. There is thus little economic incentive for the utilities to help their customers to implement energy-efficiency measures. If the customers are improving their energy performance, encouraged by environmental targets and potential economic benefits, the utilities risk to encounter other losses from not participating in the process. Utilities can take a more active role in ensuring that the implemented energy-efficiency measures have positive effects on their district heating production. This will require them to develop business models that can decouple revenues from sold kWh of heating and focus more on providing energy as a service.

The impacts of energy-efficiency measures vary, and they will differ between district heating systems. Energy savings captured during the winter season are generally more attractive, as they lead to a more even district heating production. In some systems though, winter skewed savings significantly limit the co-generation of electricity. Furthermore, energy savings captured during the summer season are more attractive in systems that have boilers dedicated for the low demand period. These circumstances suggest that local energy utilities should analyse the impacts of energy-efficiency measures on their individual system and act accordingly. In order to achieve energy efficiency in a manner which is favourable for all the involved actors, increased cooperation is necessary to overcome problems with split incentive structures. Most often the energy utilities try to provide incentives through their tariff design. Improved design of the district heating price models can provide better incentives for efficiency improvements, but these models are often complex and can be too difficult for the property owners to fully understand. In order to influence decisions on measure choices, energy suppliers should preferably offer consultation services to property owners. Stakeholder participation can create synergies. By participating with a greater commitment to implementing energy-efficiency strategies in the residential building sector, energy utilities can work with their customers to avoid the burden of measures that will have a significant negative impact on district heating system efficiency. Energy utilities can participate in different ways, e.g. by providing their customers with knowledge on the relationships between energy efficiency, indoor environments, and energy demand, or by restructuring company operations to include the implementation of energy-efficiency measures (and thus become true energy service companies, known as ESCO). The incentives for property owners include lower energy bills and environmentally adapted heating, while the benefits for the utilities are lower costs, reduced environmental impact and more satisfied customers, and the residents in general would benefit from, e.g., a better indoor environment quality and better health.

It is important to note that this assessment is based on a short-term analysis in which fixed district heating capacities were assumed. Winter skewed energy savings and decreases in the maximum heat demand in buildings can have further benefits in the long run. This is valid especially for growing municipalities. Instead of building new plants, the energy utilities will be able to serve and supply district heating to more customers from the existing capacity. District heating and co-generation plants enjoy economies of scale, but in order to overcome inefficiencies, this requires long-term operation, implying that an aspiration towards winter skewed energy savings in many cases contributes to a cost-effective production in the long run.

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Compliance with ethical standards

Conflict of interest The authors conducted the research while employed at WSP Sweden. A reference group made up of energy utility and housing sector representatives followed the research project and discussed the findings in the course of the research project.

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