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Balancing investments in building energy conservation measures with investments in district heating – A Swedish case study

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ABSTRACT

We investigate the cost-optimal mix of reduction in the space heating (SH) demand in buildings, achieved through investments in energy conservation measures (ECMs), and investments in the local district heating (DH) system. The work includes three modeling scenarios, which differ with respect to SH demand reduction targets (no supply side targets) for buildings: without a target (only fuel price drives demand reduction); with a total demand reduction (for the building stock); and with a specific demand reduction (to reach a specific kWh/(m^2•y) value for individual buildings). Special emphasis is placed on the choice of ECMs in buildings. For the scenario without a target for SH demand reduction, the least-cost option is a combination of investments in ECMs, heat generation and in storage technologies, yielding a SH demand reduction of 24% already by Year 2030, and thereafter a decrease of 28% up to Year 2050. The reductions are achieved mainly through investments in ventilation heat recovery systems and insulation of roofs. The scenarios that include SH demand reduction targets give similar demand reductions of about 60% by 2050, as compared to 2020. However, the investment cost for fulfilling the specific target scenario is higher than that for the total target scenario.

1. Introduction

With the aim of improving the energy performance of buildings, the European Commission established the Energy Performance of Buildings Directive (EPBD), which requires that all new buildings be" nearly zero-energy" buildings by Year 2020. However, buildings are long-term assets, and in the EU 75%–90% of the buildings standing today are expected to be still in use in Year 2050 [1]. As energy use is strongly linked to the age of the building, there is a significant energy saving potential associated with upgrading building envelopes and heating and cooling systems to modern standards. According to the amendments introduced to the EPBD from Year 2018, energy efficiency improvements and deployment of renewables should be prioritized during building renovations [2]. It is also stated that building renovations at an average rate of 3% annually will be required to accomplish the EU's energy efficiency ambitions. This can be compared to the current renovation rate estimated as just over 1% (for all buildings) [1].

In Sweden, 39% of the total final energy use is attributed to the residential and service sectors [3]. Following the EPBD, there are corresponding Swedish targets for energy efficiency in buildings that prescribe decreases in total energy use in all (existing and new) buildings of 20% by Year 2020 and 50% by Year 2050, as compared to the level of usage in Year 1995 [4]. More recently, in Sweden's Draft Integrated National Energy and Climate Plan [5], the Swedish building renovation strategy states that the specific energy use should be limited to 90 kWh/(m^2·y), 85 kWh/(m^2·y), and 80 kWh/(m^2·y) in new or renovated single-family dwellings (SFDs), multi-family dwellings (MFDs), and non-residential buildings (NRBs), respectively, by Year 2030. Currently, Swedish residential and non-residential (only statistics for office buildings are available) buildings use on average 235 kWh/(m^2·y) and 169 kWh/(m^2·y) of energy (space heating (SH) accounting for around 60% of this amount), respectively [6]. Thus, even though pieces of legislation can have different metrics (total vs. specific energy use), it is clear that substantial reductions in the energy used in buildings are required to meet the European and/or Swedish energy use reduction targets.

Whereas the majority of studies that have investigated the effects of building retrofitting and energy conservation measures (ECMs) on the energy performance of buildings (exemplified by [7–11]) have not taken the supply side into account, EPBD requires that "*Member States should seek a cost-efficient equilibrium between decarbonizing energy supplies and reducing final energy consumption*" [2]. In Sweden, district heating (DH) accounts for 46% of the final

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energy use in the residential and service sectors [3], with market shares of the total final heat supplies to multi-family residential houses and service sector buildings of 89% and 80%, respectively [12]. Thus, finding synergies between energy retrofits in buildings and the generation of heat in DH systems is crucial for the success of urban heat strategies [13]. There are studies that have investigated the effects of ECMs in buildings on the operation of DH systems (exemplified by [14–18]), i.e., one-directional impacts of demand-side changes on the supply side. The study conducted by Difs et al. [14] for example, has investigated the effects of the following three ECMs (one at a time): heat load control, attic insulation, and more efficient electrical appliances, on the local DH supplier, consumers, and on the DH supplier and consumers together (using a local energy system perspective) in the city of Linköping, Sweden. Difs and colleagues have concluded that the heat load control and electricity saving measures are economically beneficial from the local energy system perspective, while attic insulation is profitable from the consumer perspective. Blomqvist et al. [15] have investigated the effects on the operation of the DH system of Linköping, Sweden of five building renovation scenarios, including ECMs for building envelopes, ventilation systems, and the substitution of DH with a ground-source Heat Pump (HP). They have concluded that building envelope ECMs have limited potential, due to the already low U-values of the studied buildings, while ventilation measures provide greater improvements in building energy performance. Sperling and Möller [19] and Delmastro et al. [20] have applied an integrated approach to the local energy systems of Frederikshavn, Denmark [19] and Torino, Italy and Stockholm, Sweden [20], in which the implementation of ECMs and the expansion [19] or modernization [20] of DH systems were taken into account simultaneously. Both of these studies have reported that scenarios in which end-use energy savings are combined with developments of the DH systems result in improved overall fuel efficiency [19] and the optimal combination of total system cost and emissions reductions [20].

Whereas most of the abovementioned studies have focused on the effects of ECMs on the operation of DH systems [14–18], only a few studies have investigated the development of local energy systems while considering both the implementation of ECMs and the expansion/modernization of DH systems [19,20]. However, these studies used exogenously defined combinations of demand and supply investments. Thus, there is a lack of studies of the trade-offs between building renovation strategies and development of DH systems. The method applied in the present work relies on optimization modeling, which minimizes the total system cost and allows for investments in ECMs and heat generation/storage technologies in a city-scale energy system up to Year 2050 (no pre-defined combinations of investments are applied). None of the abovementioned studies assures feedback loops between the demand and supply sides. This will require that the results from the building simulations are fed into the DH system modelling. The method applied in this work estimates the hourly SH demand from buildings together with the optimal dispatch of heat generation/storage technologies, i.e., integrated demand and supply optimization, while identifying the cost-optimal combination of future investments in both the buildings and the supply system. The work is based on three modeling scenarios, with one cost-minimal local energy system development scenario and two scenarios with energy use reductions targets in the buildings, i.e., total and specific SH demand reductions. The following research questions are addressed: 1) What is the cost-optimal balance between the implementation of ECMs in buildings and development of DH systems?; 2) Which ECMs are cost-effectively implemented and what are the effects of their implementation on the energy performance of buildings?; and 3) What are the consequences of setting a demand reduction target on the total energy use in buildings, as compared to setting a specific target per heated floor area?

This paper is organized as follows: Section 2 outlines the modeling approach applied and the case study, together with the modeling scenarios investigated in this work; Section 3 describes the results obtained from the modeling; Section 4 further discusses these results; and Section 5 summarizes the conclusions drawn from the study.

2. Methodology

This paper uses techno-economic modeling, which is applied to a regional case study in the form of the building stock (BS) and DH system of the City of Gothenburg, Sweden, as described below.

2.1. Modeling approach

The techno-economic, linear optimization model applied in this work is a refinement of the dynamic Energy Balance Unit Commitment (EBUC) model that was previously developed by the authors [21]. Additions made within this work include the possibility to make investments in both the demand- and supply-side technologies for several model years, and thus, this version of the model is denoted as invEBUC. The objective function of the invEBUC model is to minimize the total system cost, i.e., the sum of the running cost of the DH system and the cost for investments in both the DH system and ECMs, over the modeling time horizon[1]. The time horizon of the model is from 2020 to 2050, with investments allowed in Years 2030, 2040, and 2050. Each investment period describes a year with an hourly time resolution, i.e., the supply–demand balance is fulfilled for each hour (time-step). As a consequence, the invEBUC model estimates the hourly SH demand from buildings together with the optimal dispatch of heat generation/storage technologies, i.e., it accounts for the feedback loops between demand and supply, while identifying the cost-optimal combination of future investments in DH technologies and the ECMs applied to buildings.

The total heating demand of the system consists of the endogenously calculated SH demand from the studied BS, exemplified by representative buildings, as well as the non-SH demand and energy losses in the DH network (piping grid). The SH demand is calculated in the model through an energy balance over each representative building, which are represented in the model as a single thermal zone. The calculations include investments in ECMs and the resulting changes in the building characteristics. The calculated SH demand of each representative building is then extrapolated to represent the SH demand of the whole BS, both residential and non-residential dwellings, using BS weight coefficients. The non-SH heating demand (e.g., hot water demand from buildings and/or demand from industrial users) is assumed to be inflexible and is given to the model exogenously. The energy losses in the network are calculated based on the heat loss coefficient of the network and the average water temperature of the DH network and the ground temperature. Details of the invEBUC modeling of the total heating demand of the system are described elsewhere [21]. Appendix A gives the approach to modeling investments in ECMs applied in this work.

[1] The objective of the modeling applied in this work is limited to economic parameters, i.e., minimization of the cost, and does not include environmental targets, e.g., constraints on CO_2 emissions. Nonetheless, the objective of minimizing CO_2 emissions from the supply side, in a DH system, is addressed in this work by considering only CO_2-neutral heat generation technologies as investment options in the period 2030–2050. In general, the CO_2 intensity of Swedish DH systems is quite low, as they employ a combination of renewable fuels and industrial waste heat.

For each investment period, the model identifies the optimal unit commitment and dispatch of the heat generation units while accounting for interactions with the wholesale electricity market (not explicitly modeled within this work) via CHP plants and HPs. Binary variables previously used in the original EBUC model to represent the technical limitations of the heat generation units (minimum heat output level and start-up characteristics) are removed, and the representation of such units is in the invEBUC model linearized to limit calculation times. The linearization is achieved via a so-called 'two-variable' approach, with one variable indicating the hourly generation and one variable indicating the spinning capacity available for the generation of heat/electricity (further explained in [22,23], with part-load costs calculations modified according to Appendix B). Investments in new heat generation/storage capacities are linear, i.e., new investments can be made in any size, which in reality may be limited to standard sizes. The invEBUC model has perfect foresight and is implemented in the modeling language GAMS.

2.2. Case study

The BS of the City of Gothenburg is represented in the invEBUC model by representative buildings: 27 SFDs; 65 MFDs; and 40 NRBs[2]. The description of the modeled representative buildings is based on the BETSI (*Byggnader Energi, Tekniska Status och Inomhusmiljö*) database [24], which contains detailed descriptions of 1,800 sample (existing) buildings, which are chosen by Boverket [25] and Statistics Sweden [26] as being representative of the standing Swedish BS in Year 2005. Additional archetype buildings were created to represent the buildings constructed under the period 2005–2012 (data from Year 2012 are used in this work for the modeling of the period 2020–2050, unless stated otherwise). A more detailed description of how the representative buildings and their respective weight coefficients were chosen for the present work can be found in a previous publication [21].

The current generation mix of the DH system of the City of Gothenburg is represented by 13 aggregated heat generation units, including CHP plants, heat-only boilers (HOB), and HPs, with the base load being covered by the waste heat from two refineries and a municipal waste incineration plant. All the CHP plants are modeled with a fixed power-to-heat ratio. The coefficient of performance (COP) values of the HPs are calculated based on the temperature profiles of the available heat sources, i.e., sewage or outdoor air, and a heat sink, i.e., DH system supply water (further explained in [27]) and, thus, have hourly values. Assumptions regarding the technical and economic parameters that describe the existing heat generation units of the DH system of Gothenburg can be found elsewhere [21]. The energy losses in the DH heat exchangers (substations) in the buildings are assumed to be 10% [20]. Although the DH system of Gothenburg is connected to two neighboring municipalities, heat imports to and exports from these municipalities are not included in the modeling, as the level of exchange is low.

2.3. Investigated scenarios

To study the impacts of ECMs on the energy demand reduction potentials in the existing BS and operation/development of DH systems, three scenarios with different requirements for the reduction of SH demand in buildings are investigated.

[2] Non-residential building types are: 1) hotels, restaurants, office/administration, food commerce, and other commercial buildings; 2) healthcare 24/7, other healthcare; 3) educational; 4) dwellings, religious practice buildings, garages; and 5) sports centers, cultural centers, and other.

The *Reference* scenario represents a least-cost energy system development path without any prescribed targets for SH demand reductions, which entails identifying the most cost-beneficial investments for both the demand and supply sides from the local energy system perspective. Thus, no SH demand reduction targets are applied.

The *Total Demand Reduction (Tot.Dem.)* scenario prescribes reduction targets for the total SH demand in the BS, which should decrease by 25%, 45%, and 60% by Years 2030, 2040, and 2050, respectively, as compared to Year 2020. This scenario should reflect the EU targets and the energy efficiency ambition level.

The *Specific Demand Reduction* (*Spec.Dem.*) scenario sets a target for the specific SH demand reduction in the BS according to the following:

- In Year 2030, the specific SH demand in the BS should be <55 kWh/(m^2·y) (compared to today's averages of 145 kWh/(m^2·y) and 110 kWh/(m^2·y) for residential and non-residential buildings, respectively). This is under the assumption that all existing buildings will undergo refurbishments before Year 2030 and will thereby comply with the Swedish building renovation strategy targets set out in Sweden's *Draft Integrated National Energy and Climate Plan* [5]. The specific SH demand limit of 55 kWh/(m^2·y) is based on the energy use reduction target for SFDs (which is not significantly higher than the targets for MFDs and NRBs) and accounts for the ratio between the specific energy use and specific SH demand in buildings [6];
- In Years 2040 and 2050, the specific SH demands in the BS should be <45 kWh/(m^2·y) and <35 kWh/(m^2·y), respectively. This is to achieve deep renovation of buildings by Year 2050, as compared to Year 2020 (here, 'deep renovation' means that the specific energy use of buildings is reduced by at least 75% [28]).

In each scenario, several ECMs, heat generation technologies, and TES technologies are included in the invEBUC model as investment choices (listed in Table 1). The ECMs included in this work are: 1) building envelope ECMs, i.e., improved insulation and, consequently, reduced U-values for walls and roofs and replacement of windows; and 2) ventilation system-related, i.e., installation of a centralized Ventilation and Heat Recovery (VHR) system. Assumptions regarding the technical parameters, i.e., additional thermal resistance added to the building envelope components as a result of the building envelope ECMs and the efficiency of the VHR system, together with the investment costs of the ECMs are presented in Appendix C, Table C1. Assumptions regarding the technical and economic parameters that describe the heat generation and TES technologies included in the present work as investment choices in the DH system (no demand-side heat generation/storage technologies are modelled in this work) can be found in Appendix C, Tables C.2–C.4, respectively.

In all the scenarios, investments are not allowed in Year 2020, i.e., the energy balance is fulfilled for the standing BS and existing heat generation capacities in the studied DH system, due to its proximity in time. As indicated above, this work focuses on the existing BS of Gothenburg and the increase in the number of new buildings expected in the future (period of 2030–2050) is not accounted for. The heating demand not related to the SH from buildings (e.g., hot-water demand and demand from industries) is also assumed in this work to remain unchanged during the period 2030–2050.

Regarding the supply side, it is assumed that investments in new municipal wastewater-based HPs will only be possible after the existing HPs will have been retired. This is due to the limited flow rate of the wastewater treatment plant, which is already using all available wastewater. It is assumed in this work that one of the

Table 1
Energy Conservation Measures (ECMs), heat generation technologies, and Thermal Energy Storage (TES) technologies available as investment choices for the studied building stock and district heating system of Gothenburg in the scenarios developed within this work.

ECM	Heat generation technology	TES type
Wall_125 *(125 mm of extra insulation)*	Heat pump *(sewage water-based)*	Hot-water tank TES
Wall_200 *(200 mm of extra insulation)*	Heat pump *(air-based)*	Pit TES
Wall_250 *(250 mm of extra insulation)*	Electric boiler	Borehole TES
Roof_145 *(145 mm of extra insulation)*	Heat-only boiler *(wood chips)*	
Roof_245 *(245 mm of extra insulation)*	CHP plant *(wood chips)*	
Roof_345 *(345 mm of extra insulation)*	Solar heating	
Window_12 *(U-value of 1.2 W/m^2)*		
Window_11 *(U-value of 1.1 W/m^2)*		
Window_08 *(U-value of 0.8 W/m^2)*		
VHR system		

CHP, Combined heat and power; VHR, ventilation and heat recovery.

existing oil refineries will be decommissioned by Year 2040, while another will still provide waste heat to the DH system up to Year 2050 (e.g., will be converted to a bio-refinery). In addition, total heat deliveries from the oil refineries and wastewater-based HPs (existing and any new investments) are limited to 950 MW, which corresponds to a DH supply water temperature of 85 °C. This is due to technical limitations that prevent these technologies from providing higher supply temperatures (personal communication from the DH system operator).

The indoor, operative set-point temperatures in MFDs, SFDs, and NRBs are set at 21 °C, 20 °C, and 20 °C (22 °C in educational buildings), respectively, which are within the recommended operative temperature interval of 20°–23 °C [29,30]. The set-point temperature is higher in MFDs than in SFDs due to the assumption that most of the apartments are rentals and need to comply with the contractual temperature of 21 °C [29], while SFDs are owned by the residents and have the set-point temperature at the lowest allowed value. The indoor air set-point temperature is set 1.5 °C higher than the operative temperature: giving set temperatures for the MFDs, SFDs, and NRBs of 22.5 °C, 21.5 °C and 21.5 °C (23.5 °C in educational buildings), respectively, based on the findings reported elsewhere [29,31].

The hourly values of the supply and return water temperatures in the DH network, together with the hourly outdoor air and ground temperatures for Year 2012 are provided by the DH system operator. The solar irradiation data are obtained from the Swedish Meteorological and Hydrological Institute (SMHI) [32]. The hourly day-ahead electricity spot prices from Year 2012 are taken from the Nordic electricity market *Nordpool* [33] and are used as inputs for the modeled Year 2020. The hourly electricity prices (*cf.* Appendix D) and the prices for Electricity Certificates for the period 2030–2050 are extracted from the ELIN/EPOD modeling package [34,35]. The fuel prices for the existing heat generation units are obtained from the Swedish Energy Agency [36], with the exception of the prices for bio-oil and natural gas, which are assumed based on the data from purchase contracts. The energy and carbon taxes are taken from Nordenergi WG [37].

To verify the robustness of investment choices made between electricity-consuming units (HPs and electric boilers) and electricity-generating units (CHP plants) in the modeled DH system, two additional model runs are performed with the *Reference* model setup but with lower (biomass prices remaining at today's level of around 20 €/MWh in the period 2030–2050) and higher (biomass prices of 50 €/MWh, 60 €/MWh, and 80 €/MWh in Years 2030, 2040, and 2050, respectively) biomass prices, as compared to the prices used in the investigated scenarios (*cf.* Table C3, Appendix C).

3. Results

3.1. Optimal combination of ECMs and DH investments

The results of the modeling exercise reveal, already in the *Reference* scenario (i.e., the scenario without SH demand reduction targets), that the least-cost development scenario for the local energy system of Gothenburg is achieved via a combination of investments in ECMs in buildings and in heat generation and storage technologies in the DH system. From Fig. 1, it is clear that in the *Reference* scenario, SH demand savings of up to 24% should be implemented in the BS of Gothenburg already by Year 2030 as this would be cost-effective. Most of the savings, i.e., 22p.p. (percentage points), are attributed to the installation of VHR systems in MFDs and NRBs, while an additional 2 p.p. of savings are linked to the insulation of roofs (further explained in Section 3.2). It is also evident that there is little additional investment in ECMs in Years 2040 and 2050 in the *Reference* scenario, since they are not economically beneficial.

Fig. 1 shows that by Year 2050 the total modeled SH demand from the BS of Gothenburg is reduced by 60% and 54% in the *Tot. Dem.* and *Spec.Dem.* scenarios, respectively, which is in line with the set targets. This indicates that meeting the Swedish energy demand reduction targets will result in lower final energy savings in buildings than would meeting the European targets. However, it should be noted that some buildings (41% of SFDs in Year 2030 and up to 57% of SFDs, 4% of MFDs, and 29% of NRBs in Year 2050) are not able to meet the specific SH demand reduction target in the *Spec.Dem.* scenario even when all available ECMs of each type are implemented. Thus, insulation of other building envelope components, e.g., basements (not investigated in this work), or the possibility to invest in ECMs with better energy performance are among the measures that could help to meet the target.

Fig. 1 shows that by Year 2030, the SH demand savings in the *Spec.Dem.* scenario are greater than those in the *Reference* and *Tot.Dem.* scenarios. Most of these additional savings are attributed to significantly larger investments in all types of ECMs in SFDs, which are currently characterized as the building category with the highest specific SH demand in the BS of Gothenburg (*cf.* [21] for more details). The results show that by Year 2040, almost all the buildings in Gothenburg should be equipped with VHR systems in both the *Tot.Dem.* and *Spec.Dem.* scenarios. Regarding the building envelope ECMs, the SH demand savings of 32p.p. in the *Tot. Dem.* scenario by Year 2050 are achieved mainly due to extensive insulation of roofs and replacement of windows in all building types. In the *Spec.Dem.* scenario, investments in building envelope ECMs are spread more evenly across the building categories, with investments in the insulation of roofs and replacement of windows still prevailing over the insulation of walls.

Fig. 2 shows the development of the heat generation/storage capacity and the amount of generated heating energy in the DH system of Gothenburg up to Year 2050, as obtained from the invE-BUC modeling. The mix of heat generation technologies and TES is shown; it is clear that a combination of HPs, electric boilers, and pit TES reflects cost-optimal generation and storage capacity by Year 2050 in all the scenarios. By Year 2030, almost 50% of the existing heat generation capacities are assumed to be retired due to age.

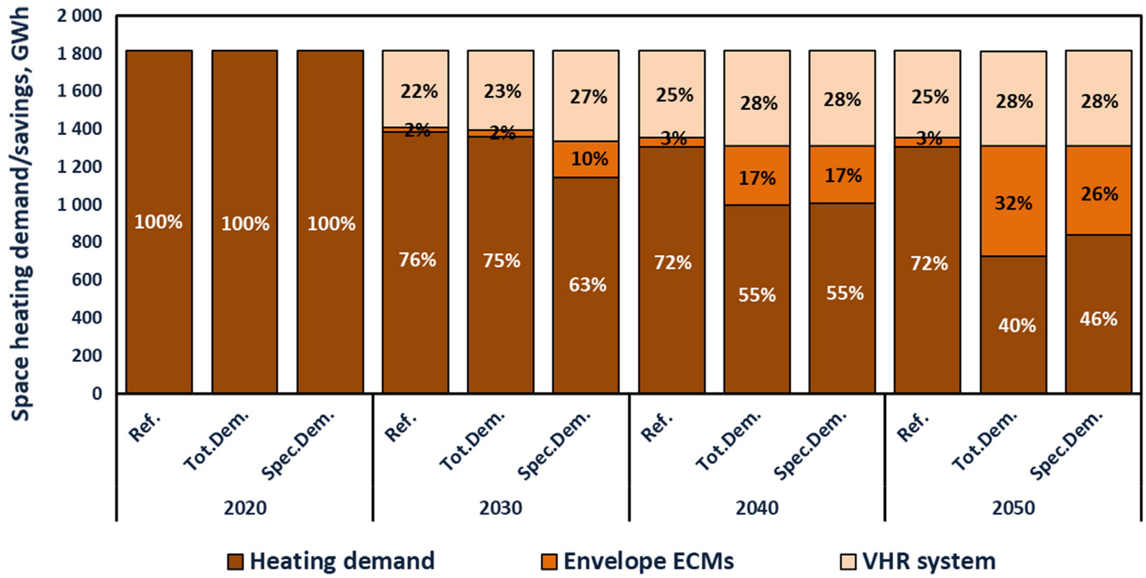

Fig. 1. Space heating demand and space heating demand savings in the studied building stock of Gothenburg in the period 2020–2050, as obtained through invEBUC modeling of the *Reference*, *Tot.Dem.* and *Spec.Dem.* scenarios. Note that the presented space heating demand savings in the *Spec.Dem.* scenario account for the fact that not all of the buildings have met the target.

However, no investments take place in new heat generation technologies in any of the scenarios. Instead, pit TES with total storage capacity of 60 GWh in the *Reference* and *Tot.Dem.* scenarios and of 55 GWh in the *Spec.Dem.* scenario is installed to balance the demand and supply. By Year 2040, the capacity of the pit TES increases to 100 GWh in the *Reference* scenario and to 77 GWh in the *Tot.Dem.* and *Spec.Dem.* scenarios. Considering the C-factor of the pit TES applied in this work, these values for the total storage capacity of the pit TES correspond to approximately 475 MW and 370 MW of charge–discharge capacity of the TES, which are considered reasonable for the size of the DH system investigated. The observed energy level profile of the TES shows that it serves both as long-term (seasonal) storage, i.e., stores heating energy from summer to winter, and as short-/mid-term storage.

The results from the modeling show that both the installed capacity and the amount of generated heating energy in the *Spec. Dem.* scenario, as well as in the *Tot.Dem.* scenario, are substantially lower than the capacity and demand in the *Reference* scenario, due to the prescribed lower SH demands in the former scenarios. It can be observed from Fig. 2 that by Year 2050, more than half of all the heating energy in the DH system in all the scenarios comes from the waste incineration plant and the remaining industrial waste. The remaining heating energy is mainly generated by HPs, with investments made in both Year 2040 and Year 2050. The installed capacity of electric boilers by Year 2050 is equal to the capacity of HPs in the *Reference* scenario and is 50% larger than the capacities of the HPs in the *Tot.Dem.* and *Spec.Dem.* scenarios. However, the amount of heating energy generated by electric boilers is at least 5-fold smaller than that from HPs. This is because the electric boilers are used exclusively for covering the peaking demand during short periods of time.

The DH system composition shown in Fig. 2 depends on the assumptions made regarding electricity and biomass prices. The results of the additional model run with the *Reference* model setup but with biomass prices during the period of 2030–2050 being at the current level – around 20 €/MWh – reveal that the future cost-optimal heat generation capacity mix of the studied DH system entails investments in CHP plants rather than in HPs, as in the *Reference* scenario with default biomass prices of 40, 45, and 50 €/MWh in Years 2030, 2040, and 2050, respectively. At the same time, the types and the extent of implementation of ECMs in buildings in this additional model run are similar to those in the *Reference* scenario, i.e., mainly the installation of VHR systems followed by the insulation of roofs. The results of the additional model run with the *Reference* model setup but with biomass prices during the period of 2030–2050 being higher than the default values show that the investments made in the DH system and in the BS are identical to those seen in the *Reference* scenario. These results indicate that the relationship between electricity and biomass prices used in the present work influences the type of heat generation technologies that will attract investment in the DH system, whereas the overall levels of prices for energy (both for electricity and biomass) should increase so as to trigger further investments in ECMs in buildings.

The results from the modeling indicate that if the European (*Tot. Dem. scenario*) or Swedish (*Spec.Dem. scenario*) energy demand reduction targets in buildings are to be met, significantly larger investments in ECMs will be required, as compared to the *Reference* scenario. This is expected, since in the *Reference* scenario, only fuel price drives demand reduction and, thus, a lower demand reduction is achieved.

Table 2 shows that, in order to meet the target, significant investments in ECMs in the *Spec.Dem.* scenario are required already by Year 2030. This indicates that meeting the Swedish energy demand reduction targets for buildings may require more prompt and substantially larger financial support, e.g., via subsidy schemes, as compared to the European targets, if those targets are to be met. From Table 2, it is evident that the sum of investments in ECMs and heat generation/storage technologies over the whole modeling period is greater in the *Spec.Dem.* Scenario than in the *Tot.Dem.* scenario, while the reduction in total SH demand by Year 2050 is 6p.p. lower (*cf.* Fig. 1). The fact that in the *Spec. Dem.* scenario several buildings are not able to meet the specific SH demand reduction target, even with the ECMs that generate the largest energy savings when installed, indicates that even larger investments may be needed to meet the target in all the buildings. This shows that policies that target the total energy use reductions have the potential to achieve the same energy savings at a lower cost than policies that are focused exclusively on the specific energy use in buildings.

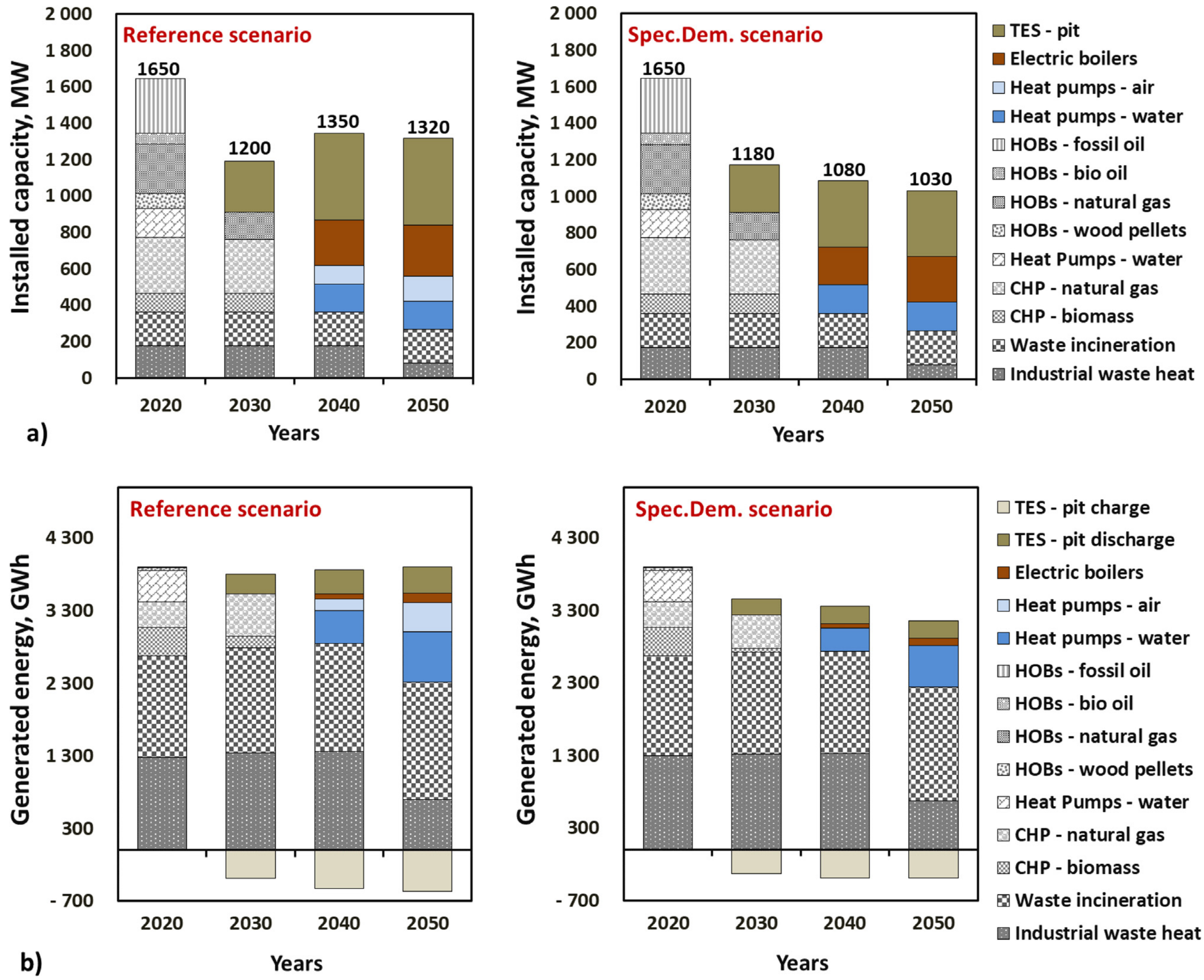

Fig. 2. Installed capacity (a) and generated (charged/discharged for TES) heat (b) from the heat generation/storage technologies in the district heating system of Gothenburg in the period 2020–2050, as obtained through invEBUC modeling of the *Reference* and *Spec.Dem.* scenarios. The installed capacities and generated heating energy of the *Tot.Dem.* scenario are similar to those of the *Spec.Dem.* scenario and, thus, are not shown here.

Table 2
Net present values of the total investment costs of the energy conservation measures (ECMs), heat generation units, and thermal energy storage (TES) units invested in the studied building stock and district heating system of Gothenburg, as obtained through invEBUC modeling of the *Reference*, *Tot.Dem.*, and *Spec.Dem.* scenarios.

Year	Measure(s)	*Reference* *mln€*	*Tot.Dem* *mln€*	*Spec.Dem* *mln€*
2030	ECMs	8.9	10.9	356.1
	VHR system	63.5	68.8	122.3
	Heat generation	–	–	–
	TES	14.6	14.5	13.7
2040	ECMs	6.5	311	170.3
	VHR system	12.4	33.7	5.0
	Heat generation	60	37.5	37.3
	TES	6.2	2.8	3.1
2050	ECMs	–	352.2	209.5
	VHR system	–	2.5	–
	Heat generation	4.7	0.2	0.5
	TES	–	–	–
Total		176.8	834.1	917.8*

* Note that not all the buildings can meet the prescribed target even by investing in all the ECMs included in the model.

The results show that the objective function values (investment and operational costs over the modeling time horizon) are 28% and 30% higher in the *Tot.Dem.* and *Spec.Dem.* scenarios, respectively, as compared to the *Reference* scenario. Thus, obviously the least costly development for the BS and the DH system is achieved if no targets are set for SH demand reductions. Nevertheless, in this scenario, the fuel price development still results in significant demand reductions (24% reduction) until Year 2030, which is in the same order as the reductions seen in the *Tot.Dem.* and *Spec.Dem.* scenarios. When aiming for further demand reductions in Years 2040 and 2050, only a small additional demand reduction can be expected from the fuel price alone (*cf.* Fig. 1). Thus, additional costs must be included in line with those of the *Tot.Dem.* and *Spec.Dem.* scenarios.

3.2. Improved energy performance of buildings and the choice of ECMs

The results of the modeling show that the investigated ECMs have the potential to improve significantly the energy performance of the buildings. Fig. 3 shows the distribution of the total heated floor area of the BS of Gothenburg across the ranges of the specific SH demand, as obtained from invEBUC modeling of the *Reference* and *Tot.Dem.* scenarios. The modeling results indicate that in Year 2020, most of the total heated floor area of the studied BS, i.e., >18 mln. m^2 (out of a total of 23.5 mln. m^2), has a specific SH demand in the range of 55–100 kWh/(m^2·y). The heated floor area of the buildings with specific SH demand >100 kWh/(m^2·y) represents around 10% of the floor area in the case investigated. It is noteworthy that around 3 mln. m^2 (13%) of the total heated floor area of the BS has a specific SH demand of <55 kWh/(m^2·y) already in Year 2020, which corresponds to the Swedish target for Year 2030.

Fig. 3 shows that the most significant improvements in the energy performance of buildings in the *Reference* scenario occur between Years 2020 and 2030, i.e., the heated floor area of buildings with specific SH demand of <55 kWh/(m^2·y) increases to 50% of the total heated floor area. In the *Tot.Dem* scenario, improvements in the energy performance of buildings by Year 2030 are similar to the improvements seen in the *Reference* scenario (*cf.* also Fig. 1). In the *Spec.Dem.* scenario, the target for SH demand in buildings of 55 kWh/(m^2·y) by Year 2030 is set for all the buildings, which is fulfilled in that scenario (except for the buildings that did not meet the target, representing 1% of the total heated floor area). By Year 2050, up to 82% of the total heated floor area of the BS investigated has a specific SH demand of <35 kWh/(m^2·y) in the *Tot.Dem.* scenario. In the *Spec.Dem.* scenario, 6% of the heated floor area does not meet the target, while the remaining buildings have a specific SH demand of <35 kWh/(m^2·y). Thus, even though the number of buildings with a specific SH demand <35 kWh/(m^2·y) by Year 2050 is higher in the *Spec.Dem.* scenario, as compared to the *Tot.Dem.* scenario, the total SH demand savings are greater in the latter (*cf.* Fig. 1). This is because in the *Spec.Dem.* scenario, most of the buildings acquire a level of investment in ECMs that is just sufficient to meet the target, while in the *Tot.Dem.* scenario many of the buildings become suitable for deep renovations, so their specific SH demand is decreased to 13 kWh/(m^2·y).

Fig. 4 shows the overall U-values, sorted in descending order, for the representative buildings of the BS of Gothenburg, as obtained from the modeling of the *Reference*, *Tot.Dem.* and *Spec. Dem.* scenarios. In the *Reference* scenario, only the buildings with the highest overall U-values in Year 2020 show improved thermal performance by Year 2030, with further minor improvements by Year 2040 and no further improvements leading up to Year 2050. By Year 2030, the U-values of the buildings decrease to a greater extent in the *Spec.Dem.* scenario than in the *Tot.Dem.* scenario. This is mainly due to the reduced U-values of SFDs, which require the largest improvements in the U-values of the building types investigated, given that these buildings currently have poorer energy performance and need to achieve greater reductions in the specific SH demand, as compared to other building types. In both the *Tot. Dem.* and *Spec.Dem.* scenarios, the average U-values of the studied buildings improve over time to the same extent, i.e., the average U-value of the studied BS (accounting for the weight coefficients) decreases from around 0.51 W/(m^2·K) in Year 2020 to 0.31 W/(m^2·K) in Year 2050 for both the *Tot.Dem.* and *Spec.Dem.* scenarios. Nonetheless, the average U-values of the building types differ between the scenarios, i.e., in the *Tot.Dem.* scenario the average U-values of the SFDs and MFDs decrease by 34% and 44%, respectively, by Year 2050, as compared to Year 2020, while in the *Spec Dem.* scenario, the average U-values of these building types decrease by 42% and 31%, respectively (the average U-values of the NRBs change to similar extents in both scenarios).Fig. 5.

The results of the modeling show that the most economically feasible building envelope ECM to apply to the investigated BS is the insulation of roofs. However, to reach both the European (*Tot. Dem.* scenario) and Swedish (*Spec.Dem.* scenario) SH demand reduction targets for buildings, a combination of ECMs will be necessary. Table 3 shows that the insulation of roofs is the only envelope ECM implemented in the *Reference* scenario, with the extent of implementation reaching 0.11, i.e., 11% of the total roof area of the BS (a few SFDs and MFDs) is chosen to be insulated, by Year 2050. This reflects the economically feasible threshold of investments in envelope ECMs, given the costs for energy in the scenarios investigated, from the local energy system perspective.

In both the *Tot.Dem.* and *Spec.Dem.* scenarios, all types of envelope ECMs are implemented in all buildings by Year 2050. However, the extent of implementation and the prioritization of ECMs throughout the investment periods are different. Table 3 shows that significantly larger investments in all three types of ECMs are made in the *Spec.Dem.* scenarios already by Year 2030, while for that year the results for the *Tot.Dem.* scenario are similar to those of the *Reference* scenario, i.e., only the insulation of roofs is implemented. The superior economic feasibility linked to the insulation of roofs is also clear from the investments made in the *Tot. Dem.* scenario by Year 2040, i.e., almost 80% of the total roof area is upgraded, which can be compared to only 5% and 9% upgraded areas of walls and windows, respectively. By Year 2050, most of the buildings in the *Tot.Dem.* scenario undergo insulation of roofs and replacement of windows, while insulation of walls is mainly implemented in SFDs and MFDs built before 1980 and having a U-value of walls of $\geq$0.5 W/(m^2·K). These results reveal that investments in the insulation of roofs and replacement of windows prevail over the insulation of walls in the *Tot.Dem.* scenario.

In the *Spec.Dem.* scenario, the prioritization of ECMs, e.g., investments in the insulation of roofs prior to the insulation of walls, cannot be as easily identified as in the *Tot.Dem.* scenario. This is because it is not possible to fulfill the specific SH demand reduction target, which is applied to each building individually, by implementing only one type of ECM, e.g., only insulating the roofs. Thus, implementation of several ECMs in package form is required to meet the Swedish energy demand reduction targets. The consequences of such ECM packages are that the BS's average U-values of walls, roofs, and windows decrease in the *Spec.Dem.* scenario by 29%, 62%, and 37%, respectively, by Year 2050, as compared to Year 2020.

Noticeably, in both the *Tot.Dem.* and *Spec.Dem.* scenarios, the roofs of some buildings get insulated with 345 mm of insulation (added thermal resistance of 8.21 K·m^2/W) in Year 2040. This is after they have been insulated with 145 mm of insulation (added thermal resistance of 3.45 K·m^2/W) in Year 2030. At the same time, some other buildings, e.g., MFDs built after 1990 s with U-values for the roofs of $\leq$0.13 W/(m^2·K), do not get any investments in roof-related ECMs in any of the years. These results indicate that the difference in the energy performance of the buildings is significant and that for some, mainly older buildings, multiple gradual energy performance improvements of, e.g., roofs, may be needed before they reach the performance levels of newer buildings. Whereas insulation of roofs is an additive type of ECM,

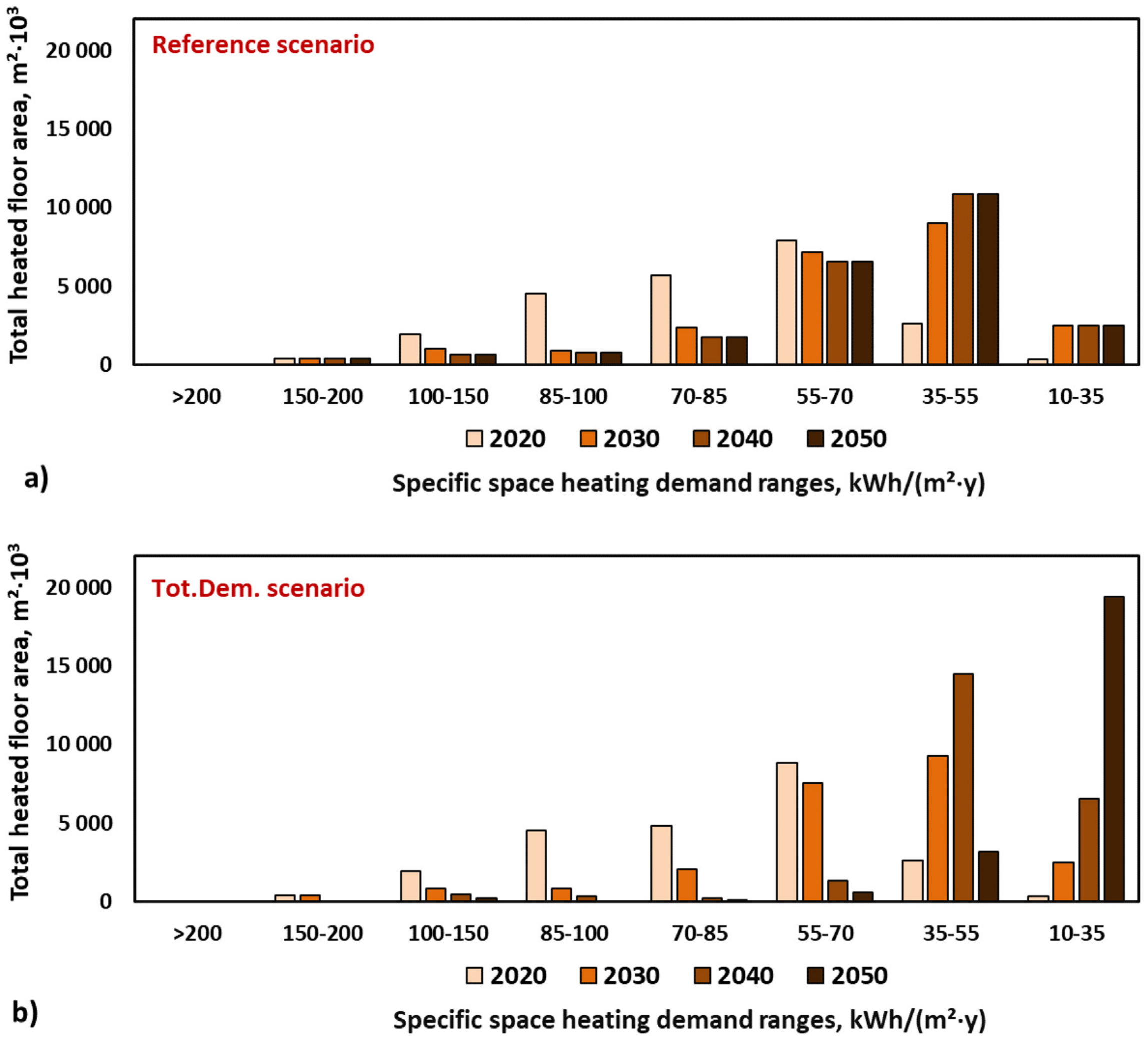

Fig. 3. Total heated floor area of the BS of Gothenburg, categorized according to the specific SH demand ranges, as obtained through invEBUC modeling of the (a) *Reference* and (b) *Tot.Dem.* scenarios. Note that the results are not shown for the *Spec.Dem.* scenario because the target is fulfilled and, thus, the total heated floor areas of the buildings in Years 2030, 2040, and 2050 lie within the ranges of 10–35 and 35–55 kWh/(m^2·y), as prescribed by the Swedish target.

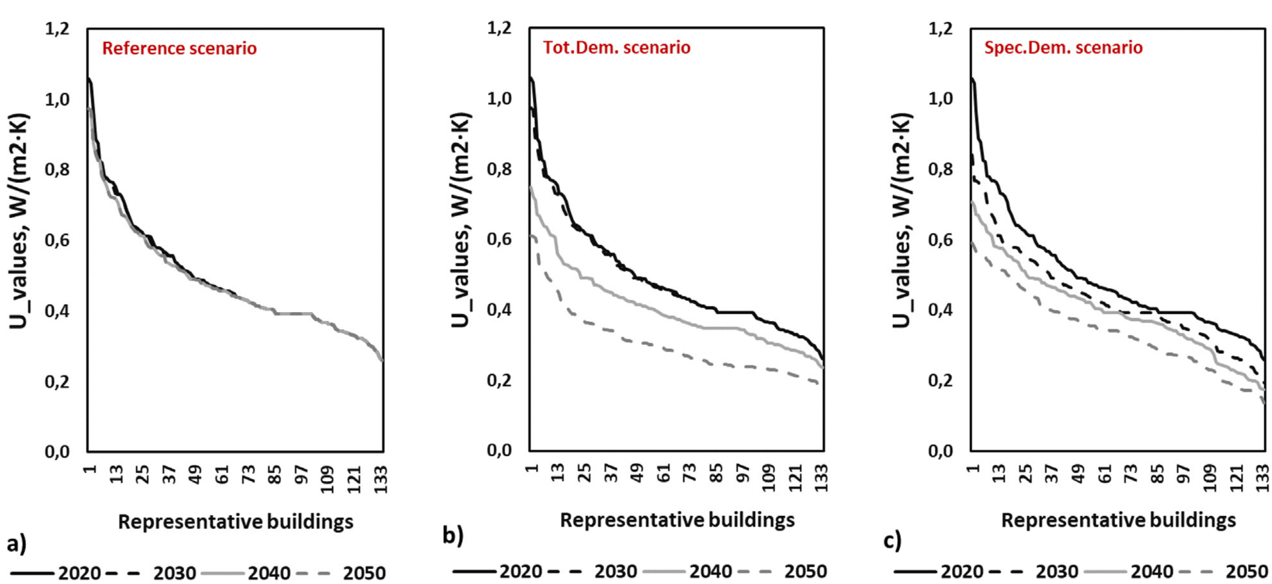

Fig. 4. Overall U-values, sorted in descending order, for the investigated representative buildings of the BS of Gothenburg, as obtained from the modeling of the (a) *Reference*, (b) *Tot.Dem.* and (c) *Spec.Dem.* scenarios. Note that the U-values are sorted in descending order individually for each investment period, which means that the order of the representative buildings in different investment periods is not necessarily the same, and thus, the building numbers cannot be compared between graphs.

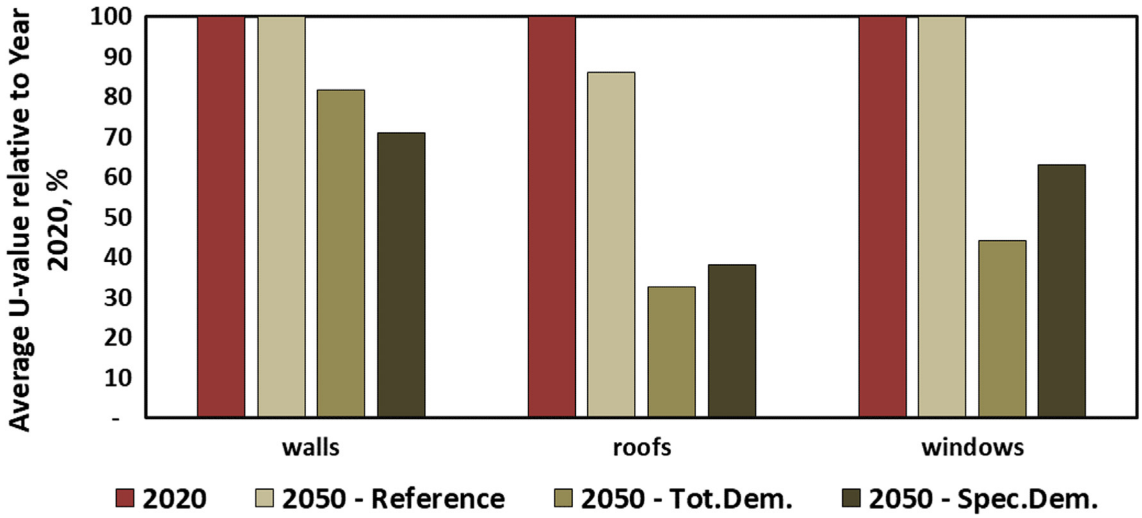

Fig. 5. Change, from Year 2020 to Year 2050 in the U-value of the building envelope components – walls, roofs, and windows – averaged over the investigated BS of Gothenburg, as obtained from the modeling of the *Reference*, *Tot.Dem.*, and *Spec.Dem.* scenarios. The U-values of the building envelope components in Year 2020 correspond to 100%.

Table 3
The UI coefficients, i.e., coefficients that indicate the extent of implementation of an ECM in a building envelope component, averaged over the studied BS of Gothenburg, as obtained from the modeling of the *Reference*, *Tot.Dem.* and *Spec.Dem.* scenarios. The value of "1" is the maximum value and indicates that 100% of a building envelope component surface is equipped with the ECM corresponding to that UI coefficient. The '*Start*' value represents the current state (U-value) of a building envelope component, i.e., if it has a value of 1, no ECMs were implemented.

	Wall-related ECMs				Roof-related ECMs				Window-related ECMs			
	'Start'	*'125 mm'*	*'200 mm'*	*'250 mm'*	*'Start'*	*'145 mm'*	*'245 mm'*	*'345 mm'*	*'Start'*	*'1.2 W/m²'*	*'1.1 W/m²'*	*'0.8 W/m²'*
Reference scenario												
2020	1	–	–	–	1	–	–	–	1	–	–	–
2030	1	–	–	–	0.94	0.06	–	–	1	–	–	–
2040	1	–	–	–	0.88	0.11	0.01	–	1	–	–	–
2050	1	–	–	–	0.88	0.11	0.01	–	1	–	–	–
Tot.Dem. scenario												
2020	1	–	–	–	1	–	–	–	1	–	–	–
2030	1	–	–	–	0.92	0.08	–	–	1	–	–	–
2040	0.95	0.05	–	–	0.21	–	0.52	0.27	0.91	–	–	0.09
2050	0.72	0.13	0.15	–	0.04	–	0.17	0.79	0.12	–	–	0.88
Spec.Dem. scenario												
2020	1	–	–	–	1	–	–	–	1	–	–	–
2030	0.71	0.04	0.02	0.23	0.30	0.01	0.30	0.39	0.60	–	–	0.40
2040	0.61	0.09	0.03	0.27	0.20	0.02	0.20	0.58	0.41	–	–	0.59
2050	0.41	0.12	0.15	0.32	0.06	–	0.21	0.73	0.21			0.79

replacement of windows requires full investment every time that replacement is made. Because of this, windows with the best performance energy-wise are chosen to be installed in the *Tot.Dem.* and *Spec.Dem.* scenarios.

The results of the modeling show that installation of VHR systems in MFDs and NRBs is economically feasible, and results in significant SH demand reductions (*cf.* Fig. 1). Table 4 shows that the extent of implementation of VHR systems in MFDs and NRBs exceeds 64% by Year 2030 in all the investigated scenarios. By Year 2050, VHR systems are installed in all the MFDs and NRBs in the *Tot.Dem.* and *Spec.Dem.* scenarios, and in 90% of the MFDs and NRBs in the *Reference* scenario. All the SFDs and a few MFDs and NRBs are not equipped with VHR systems in the *Reference* scenario due to their having a low ratio between the heated floor area and

Table 4
The average UI coefficients, i.e., coefficients that indicate the extent of implementation of a VHR system in a building ("1" is the maximum value and this indicates that a representative building is equipped with a VHR system), presented for the three buildings types, i.e., SFD, MFDs, and NRBs, as obtained from the modeling of the *Reference*, *Tot. Dem.* and *Spec. Dem.* scenarios. Buildings with VHR systems installed before Year 2020 are not presented.

Year	Reference scenario			Tot.Dem. scenario			Spec. Dem. scenario		
	SFDs	*MFDs*	*NRBs*	*SFDs*	*MFDs*	*NRBs*	*SFDs*	*MFDs*	*NRBs*
2020	–	–	–	–	–	–	–	–	–
2030	–	0.84	0.64	–	0.87	0.79	0.97	0.96	0.77
2040	–	0.91	0.93	1.0	1.0	0.98	1.0	1.0	1.0
2050	–	0.91	0.93	1.0	1.0	1.0	1.0	1.0	1.0

external surface area. In the *Tot.Dem.* and *Spec.Dem.* scenarios, investments in VHR systems are made in all building types because of the energy demand reduction targets and seemingly higher level of financial attractiveness of VHR systems over building envelope ECMs.

4. Discussion

This work focused on identifying the cost-optimal development pathway for the local DH system, considering an energy efficiency refurbishment strategy for the city's BS that involves minimizing the total system cost for both the DH and the BS. Thus, the optimization modeling applied in this work was developed to illustrate the cost-optimal relationship between the supply- and demand-side measures, which should be important information for DH operators and municipalities, as well as governments and policy-makers. In reality, the DH system operator and the BS have different owners and are governed by different policies (e.g., the EU-ETS system for the DH system and different types of taxes and building codes for the BS). This may lead to sub-optimal measures, and the present work should give some inputs to an analysis designed to identify cost-efficient policies. Clearly, the building owners want to reduce their energy bills, whereas the DH system operator wants to maximize their profit. Furthermore, the ownership form of buildings can influence the attractiveness of investments in ECMs. For example, in SFDs, the owners are usually the inhabitants and the bearers of the investment cost, as well as the beneficiaries of the reduced energy bill. In contrast, in MFDs, the owners of the buildings (investment cost bearers) are usually not the ones paying the energy bill (resulting in a "split incentive" problem). With this said, the modeling results presented in this work can be taken as an indication that: 1) well-established communication and cooperation schemes between the energy consumers and suppliers may generate economic benefits for both sides; 2) depending on the energy demand reduction target, total vs. specific, supporting schemes for energy refurbishments may need to be directed towards one or another building type, e.g., providing greater support for SFDs if a specific SH demand reduction target is set.

Regarding the supply side, the profitability of heat sales for the local DH system operator is not explicitly investigated in this work. Nevertheless, based on findings reported elsewhere [14], it can be assumed that the implementation of ECMs in buildings and, consequently, reductions of the yearly average and hourly maximum heat demands in the system will result in a lower variable cost of heat generation. This, together with increased competition from other heating options, e.g., individual heat pumps, may call for lowered DH tariffs, and consequently, lower profits for the local energy utility.

The results of this work suggest significant investments in pit TES, up to 100 GWh of storage capacity, in all the studied scenarios. This storage capacity corresponds to a TES of size >1 mln m^3, which is challenging to build. Thus, a more-detailed study is required to analyze whether a TES of such size will be chosen for the energy or capacity services. This could be done by splitting the single TES-related investment cost, as applied in this work, into two parts: capacity cost (for the heat exchanger); and energy cost (for the storage volume). However, the basis for such a split is not presented in this work.

The results also show a decrease in the CHP plant capacity (currently installed) and an increase in the capacities of the HPs and electric boilers (new investments) in the future. This could pose a challenge for the local electricity supply. Measures need to be taken to ensure that there is either sufficient grid capacity to transfer additional electricity from the transmission grid into the city or additional local electricity generation is constructed.

As for the demand side, ECMs are believed to be implemented in packages, i.e., several building components are changed/insulated at the same time. As the results indicate, more than one type of ECM is indeed implemented in the studied buildings in the *Spec. Dem.* scenario, in order to meet the target. However, In the *Reference* and *Tot.Dem.* scenarios, one ECM type - insulation of roofs - is distinctly prioritized over other ECMs and is the only ECM suggested for implementation by Year 2030. These results are dependent upon the input data used in this work, i.e., the investment cost of ECMs. However, they do not consider other, non-financial factors, such as the time to prepare and approve a refurbishment project, and the disturbance of inhabitants. Nevertheless, such clear prioritization of one ECM over other ECMS should be considered as an indication that standard refurbishment packages, if such exist and are being applied, might be reconsidered with the aim of identifying the most cost-optimal types of ECMs, as well as the extent and frequency of their implementation.

As indicated in Section 3, the modeling results suggest that the gradual (i.e., in different investment periods) implementation of ECMs of the same type but with better performance characteristics is an economically sound strategy for some buildings, e.g., the insulation of roofs with 145-mm-thick insulation in Year 2030 and thereafter with 345-mm-thick insulation in Year 2050. In reality, implementation of ECMs is likely to occur during the planned renovations of buildings, which can be expected to take place every 40–50 years. Thus, the question arises as to whether insulation of the same building envelope components should occur in multiple steps or that the thickest insulation should be installed from the beginning. Another assumption made in this work is that it is possible to implement each of the ECMs in all of the buildings. In practice, some building envelope component surfaces might have limited potential or be unavailable for insulation/replacement, e.g., roof insulation might be restricted by attic storage.

The investigated BS consists of SFDs, MFDs, and NRBs, represented by buildings with different physical characteristics and built in different years, so the results should be applicable to other cities in Sweden. The current DH system of Gothenburg is characterized by a high share of industrial waste heat, which is available in only some DH systems. However, with the retirement of one of the sources of industrial heat by Year 2050, the modeling results indicate that the missing capacity will be substituted by additional investments in HPs and electric boilers (no additional investments in TES). Therefore, the outcomes of this work regarding the choice of future heat generation/storage technologies and the type of ECMs and the extents of their implementation are expected to be similar for other heating systems and BSs in Sweden.

5. Conclusions

The development of a city-scale heating system, i.e., a DH system, and the building stock are investigated up to Year 2050 using a techno-economic investment model that estimates the space heating (SH) demand in buildings and optimizes the dispatch of the heat generation units, as well as investments in new heat generation/storage technologies and energy conservation measures (ECMs) in buildings. Three modeling scenarios are investigated in this work: 1) a reference scenario, without explicit SH demand reduction targets in buildings; 2) a total demand scenario, including a total SH demand reduction target (proxy of the European legislation); and 3) a specific demand scenario, which includes a specific SH demand reduction target (proxy of the Swedish legislation).

The modeling results reveal that a combination of investments in ECMs and heat generation capacities, together with new investments in heat-storage capacities yield the lowest total cost (i.e., investment and running costs) for the development of local heating systems. The results for the reference scenario indicate that SH demand savings in the investigated BS of up to 24% already by Year 2030 are economically motivated without any targets related to reducing the SH demand. These savings are mainly realized through the installation of ventilation heat recovery systems in MFDs and NRBs, along with substantial insulation of roofs in all the building types. The results also demonstrate that the cost-optimal heating technologies invested in are heat pumps, electric boilers, and a pit thermal energy storage. Nevertheless, with higher future electricity prices and/or lower biomass prices, combined heat and power plants may constitute part of the future heat generation capacity mix. The choice of scenario, i.e. implementing a specific or total SH demand reduction target, does not influence the types of heat generation/storage technologies that is invested in within the DH system.

The results show that the scenarios that have total and specific SH demand reduction targets achieve similar SH demand savings by Year 2050, as compared to Year 2020, i.e., 60% and 54% in the *Tot.Dem.* and *Spec.Dem.* scenarios, respectively. However, investments in ECMs in the *Spec.Dem.* scenario are found to have a higher total cost than those in the *Tot.Dem.* scenario. Moreover, the results show that not all of the buildings can meet the specific SH demand target, even if all the modeled ECMs are implemented. This indicates that economic feasibility is higher for policies that target an overall decrease in the energy use in buildings (European legislation), as compared to policies that focus on the specific energy use (Swedish legislation) if the goal is to reduce total energy use. The results also indicate that the insulation of roofs is prioritized over the insulation of walls or the replacement of windows in the investigated building stock. Nevertheless, all types of ECMs will be needed to achieve the SH demand reduction targets by Year 2050, a phenomenon that is especially prominent in the *Spec. Dem.* scenario. The results show that when ECMs are implemented the average U-value of the investigated building stock decreases to the same extent in both scenarios with the space heating demand reduction targets, i.e., from above 0.51 W/(m^2·K) in Year 2020 to 0.31 W/(m^2·K) in Year 2050. However, changes in the U-values of the different building types differ between the scenarios. The average U-values of SFDs and MFDs decrease by 34% and 44%, respectively, in the total demand scenario, as opposed to 42% and 31%, respectively, in the specific demand scenario. It is also evident that the installation of a ventilation heat recovery system is carried out for all building types by Year 2050 in both the total and specific demand scenarios.

CRediT authorship contribution statement

Dmytro Romanchenko: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Emil Nyholm:** Conceptualization, Methodology, Software, Resources, Writing - review & editing. **Mikael Odenberger:** Conceptualization, Supervision, Project administration, Writing - review & editing. **Filip Johnsson:** Supervision, Project administration, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The energy demand for SH in buildings is governed by the need to maintain the indoor temperature at a set-point value. Thus, the following intertemporal energy balance over the modeled buildings is applied in the model:

$$\boldsymbol{T}^{in}_{b,t,y} = \boldsymbol{T}^{in}_{b,t-1,y} + \frac{\left(\boldsymbol{q}^{heat}_{b,t,y} + \boldsymbol{q}^{tran}_{b,t,y} + \boldsymbol{q}^{vent}_{b,t,y} + \boldsymbol{q}^{int}_{b,t,y} + \boldsymbol{q}^{r}_{b,t,y} + \boldsymbol{q}^{cool}_{b,t,y}\right) \cdot \Delta t}{\boldsymbol{TC}^{tot}_{b}} \ \forall b \in \boldsymbol{B}, t \in \boldsymbol{T}, y \in \boldsymbol{Y} \tag{A2}$$

where $\boldsymbol{B}$ is the set of all modeled buildings, $\boldsymbol{T}^{in}_{b,t,y}$ is the set-point indoor temperature of building $\boldsymbol{b}$ at time-step $\boldsymbol{t}$ in investment year, $\boldsymbol{y}$. $\boldsymbol{q}^{tran}_{b,t,y}$ is the energy transfer through the building envelope (Eq. (A.3)), $\boldsymbol{q}^{vent}_{b,t,y}$ is the energy transfer through the ventilation system (Eq. (A.8)), $\boldsymbol{q}^{int}_{b,t,y}$ represents the internal energy gains (i.e., the energy from occupants, lighting, and appliances), $\boldsymbol{q}^{r}_{b,t,y}$ is the energy derived from solar irradiation, and $\boldsymbol{q}^{cool}_{b,t,y}$ is the energy transfer due to natural cooling (i.e., opening a window), all for each building $\boldsymbol{b}$ at time-step $\boldsymbol{t}$ in investment year $\boldsymbol{y}$. $\boldsymbol{q}^{int}_{b,t,y}$, $\boldsymbol{q}^{r}_{b,t,y}$, and $\boldsymbol{q}^{cool}_{b,t,y}$ are defined in the invEBUC model as described elsewhere ([21,38]), and are, thus, implemented as exogenous parameters. $\boldsymbol{TC}^{tot}_{b}$ is the total thermal mass of building $\boldsymbol{b}$ and $\Delta t$is the time-step length (1 h). $\boldsymbol{q}^{heat}_{b,t,y}$ is the energy transfer from the heating equipment in building $\boldsymbol{b}$ at time-step $\boldsymbol{t}$ in investment year $\boldsymbol{y}$, which defines the SH demand that is to be satisfied by the DH system.

The energy transfer through the building envelope depends on the U-value, i.e., the thermal transmittance, of the building envelope and is calculated as follows:

$$\boldsymbol{q}^{tran}_{b,t,y} = \boldsymbol{U}_{b,y} \cdot \boldsymbol{S}_{b} \cdot \left(\boldsymbol{T}^{out}_{t,y} - \boldsymbol{T}^{in}_{b}\right) \ \forall b \in \boldsymbol{B}, t \in \boldsymbol{T}, y \in \boldsymbol{Y} \tag{A3}$$

where $\boldsymbol{U}_{b,y}$ is the overall U-value of building $\boldsymbol{b}$ in investment year $\boldsymbol{y}$, $\boldsymbol{S}_{b}$ is the external surface area of building $\boldsymbol{b}$, $\boldsymbol{T}^{out}_{t,y}$ is the outdoor air temperature at time-step $\boldsymbol{t}$ in investment period $\boldsymbol{y}$, and $\boldsymbol{T}^{in}_{b}$ is the indoor operative temperature of building $\boldsymbol{b}$.

The overall U-value of the building envelope depends on the U-values of its components, e.g., walls, roofs, and windows, and is expressed as follows:

$$\boldsymbol{U}_{b,y} = \frac{\left(\boldsymbol{US}^{windows}_{b,y} + \boldsymbol{US}^{walls}_{b,y} + \boldsymbol{US}^{roof}_{b,y} + \boldsymbol{US}^{other}_{b}\right)}{\boldsymbol{S}_{b}} \ \forall b \in \boldsymbol{B}, y \in \boldsymbol{Y} \tag{A4}$$

where $\boldsymbol{US}^{windows}_{b,y}$, $\boldsymbol{US}^{walls}_{b,y}$, $\boldsymbol{US}^{roof}_{b,y}$, $\boldsymbol{US}^{other}_{b}$ are the products of the U-values of the windows, walls, roof, and other envelope components (U-values of other envelope components, such as floors and basements, are in this work aggregated and assumed to be unchanged) multiplied by the surface areas of the windows, walls, roof and other envelope components of building $\boldsymbol{b}$ in investment year $\boldsymbol{y}$.

In this work, ECMs that are related to building envelope components and designed to improve the U-values of walls, roofs, and windows are included in the invEBUC model as investment choices. Thus, the US-values of the building envelope components are calculated as follows (exemplified by the US-value of walls, $\boldsymbol{US}_{b,y}^{walls}$, for building $\boldsymbol{b}$):

$$\boldsymbol{US}_{b,y}^{walls} = \sum_{m \in ECM_{walls}} \left(\boldsymbol{U}_{b,m} \cdot \boldsymbol{UI}_{b,m,y} \cdot \boldsymbol{S}_{b,walls} \right) \forall b \in \boldsymbol{B}, y \in \boldsymbol{Y} \quad \text{(A5)}$$

where $\boldsymbol{m}$ is an ECM belonging to the set $\boldsymbol{ECM}_{walls}$, which is the set of all ECMs applicable to walls. $\boldsymbol{ECM}_{walls}$ is, in turn, a subset of the set $\boldsymbol{ECM}$ that represents all modeled energy conservation measures. $\boldsymbol{U}_{b,m}$ is the U-value per surface area resulting from measure $\boldsymbol{m}$ in building $\boldsymbol{b}$ in investment period $\boldsymbol{y}$. $\boldsymbol{S}_{b,walls}$ is the surface area associated with ECM $\boldsymbol{m}$ in building $\boldsymbol{b}$. $\boldsymbol{UI}_{b,m,y}$ is the coefficient that indicates the extent of implementation of an envelope ECM $\boldsymbol{m}$ in a respective building envelope component of building $\boldsymbol{b}$ in investment year $\boldsymbol{y}$. Since a few ECMs of the same type, e.g., three different insulation levels of walls, are available as investment choices in this work, the sum of the $\boldsymbol{UI}$ coefficients for each building envelope component of each building $\boldsymbol{b}$ in each investment year $\boldsymbol{y}$ must be equal to 1, as expressed as follows:

$$\sum_{m \in ECM_{walls}} \left(\boldsymbol{UI}_{b,m,y} \right) = 1 \; \forall b \in \boldsymbol{B}, y \in \boldsymbol{Y} \quad \text{(A6)}$$

Note that the $\boldsymbol{UI}$ coefficient (for both building envelope-related and ventilation system-related ECMs) can take values continuous in the range of 0–1. Since representative buildings in this work represent the whole BS of a city, i.e., each modeled representative building represents a number (from tens to hundreds) of existing buildings, the $\boldsymbol{UI}$ coefficient of, for example, walls, equal to, for example, 0.5, can be explained by assuming that half of the existing buildings that constitute a representative building will have the $\boldsymbol{UI}$ coefficient of walls equal to 1 and the other half will have the $\boldsymbol{UI}$ coefficient of walls equal to 0. Eqs. (A.5) and (A.6) are also applied to the subsets ECM_{roofs} and $ECM_{windows}$ to calculate $\boldsymbol{U}_{b,y}^{roof}$ and $\boldsymbol{U}_{b,y}^{windows}$, respectively.

The cost of ECMs for each building is calculated as follows:

$$\boldsymbol{UCost}_{b,y} = \sum_{ECM} (\boldsymbol{UI}_{b,m,y} \cdot \boldsymbol{ECM}_{inv} \cdot \boldsymbol{S}_{b,m}) \forall b \in \boldsymbol{B}, y \in \boldsymbol{Y} \quad \text{(A7)}$$

where $\boldsymbol{UCost}_{b,y}$ is the total investment cost of all ECMs applied to building $\boldsymbol{b}$ in investment year $\boldsymbol{y}$, $\boldsymbol{ECM}_{inv}$ is the individual specific (per m^2) annualized cost of each ECM $\boldsymbol{m}$. Note that investments in ECMs are modeled as additives, which means that the current thermal resistances of building envelope components are increased by the thermal resistances provided by the installed ECMs. The total investment cost of the ECMs applied to the modeled BS is calculated by multiplying the investment costs of all modeled buildings by the respective building weight coefficients.

The energy transfer through the ventilation system of a building depends on the difference between the indoor air temperature and the temperature of the ventilation air and is calculated as follows:

$$\boldsymbol{q}_{b,t,y}^{vent} = \boldsymbol{V}_c \cdot \boldsymbol{C}_p \cdot \boldsymbol{A}_{floor,b} \cdot \left(\boldsymbol{T}_{t,b,y}^{vent} - \boldsymbol{T}_b^{in\_air} \right) \forall b \in \boldsymbol{B}, t \in \boldsymbol{T}, y \in \boldsymbol{Y} \quad \text{(A8)}$$

where $\boldsymbol{V}_c$ is the sanitary ventilation flow rate, $\boldsymbol{C}_p$ is the volumetric heat capacity of air, $\boldsymbol{A}_{floor,b}$ is the heated floor area of building $\boldsymbol{b}$, $\boldsymbol{T}_{t,b,y}^{vent}$ is the temperature of the ventilation air in building $\boldsymbol{b}$ at time-step $\boldsymbol{t}$ in investment period $\boldsymbol{y}$, and $\boldsymbol{T}_b^{in\_air}$ is the indoor air temperature of building $\boldsymbol{b}$ (assumed to be constant at each time-step $\boldsymbol{t}$ in each investment period $\boldsymbol{y}$).

In this work, a single ventilation system-related ECM is included as an investment option and implies the installation of a Ventilation Heat Recovery (VHR) system. Thus, the temperature of the ventilation air entering a building is impacted by the VHR system in accordance with the following equation:

$$\boldsymbol{T}_{b,t,y}^{vent} = \boldsymbol{T}_{t,y}^{out} + \boldsymbol{\mu}_{VHR} \cdot \boldsymbol{UI}_{b,y}^{VHR} \cdot \left(\boldsymbol{T}_b^{in\_air} - \boldsymbol{T}_{t,y}^{out} \right) \forall b \in \boldsymbol{B}, t \in \boldsymbol{T} \quad \text{(A9)}$$

where $\boldsymbol{\mu}_{VHR}$ is the efficiency of the VHR system, and $\boldsymbol{UI}_{b,y}^{VHR}$ is the coefficient that indicates the extent of implementation (from 0 to 1) of the VHR system. Investments in the VHR system are governed as follows:

$$\boldsymbol{VHRcost}_{b,y} = \boldsymbol{UI}_{b,y}^{VHR} \cdot (\boldsymbol{VHRinv}_b \cdot \boldsymbol{CRF} + \boldsymbol{VHRrun}_b) \forall b \in \boldsymbol{B}, y \in \boldsymbol{Y}$$

where $\boldsymbol{VHRcost}_{b,y}$ is the total cost of installing the VHR system in building $\boldsymbol{b}$ in investment period $\boldsymbol{y}$, and $\boldsymbol{VHRinv}_b$ and $\boldsymbol{VHRrun}_b$ are the investment and running costs, respectively, of the VHR system (further explained in Appendix C, Table C1).

Appendix B

In the two-variable approach, the total cost of cycling a heat generation unit depends on the increase in spinning capacity available for generation (start-up) and the deviation of the actual generation from the spinning capacity (part load). In the invEBUC model, the start-up cost is defined as previously described [23], whereas the part-load cost is in this work calculated as:

$$\boldsymbol{PLcost}_{p,t} = \left(\frac{1}{1 - \boldsymbol{r}_p} \right) \left(\left(\frac{\boldsymbol{RUNcost}_{p,t}}{\boldsymbol{\mu min}_p} + \boldsymbol{OMcost}_p \right) + \left(\frac{\boldsymbol{RUNcost}_{p,t}}{\boldsymbol{\mu rate}_p} + \boldsymbol{OMcost}_p \right) \right) \cdot \boldsymbol{r}_p \, \forall p \in \boldsymbol{P}, t \in \boldsymbol{T} \quad \text{(B1)}$$

where $\boldsymbol{P}$ is the set of all modeled heat generation units, $\boldsymbol{T}$ is the set of all time-steps, $\boldsymbol{PLcost}_{p,t}$ is the part-load cost of heat generation from heat generation unit $\boldsymbol{p}$ at time-step $\boldsymbol{t}$, $\boldsymbol{r}_p$ is the minimal output level of a generation unit expressed as a percentage of the rated (installed) capacity, $\boldsymbol{RUNcost}_{p,t}$ is the running cost of heat generation unit $\boldsymbol{p}$ (including the fuel cost and energy and CO_2 taxes), and $\boldsymbol{OMcost}_p$ is the operation and maintenance cost of heat generation unit $\boldsymbol{p}$. $\boldsymbol{\mu\_min}_p$ and $\boldsymbol{\mu\_rate}_p$ are the efficiencies at minimum load level and at rated output, respectively, of heat generation unit $\boldsymbol{p}$.

Appendix C

Table C1
Assumed parameters for the Energy Conservation Measures (ECMs) included in the present work as investment choices in the building stock of Gothenburg. For roofs and walls, the numerical parts of the names of the ECMs indicate the thickness of the applied insulation material if the ECMs are implemented. For windows, the numerical parts of the names of the ECMs indicate the resulting U-values of the windows if the ECMS are implemented. SFDs, Single-family dwellings; MFDs, multi-family dwellings; NRBs, non-residential buildings; VHR, ventilation heat recovery.

Investment choice[1]	R_value[2], K*m[2]/W	Cost of ECMs for SFDs, €/m[2]	Cost of ECMs for MFDs, €/m[2]	Cost of ECMs for NRBs, €/m[2]
Wall_125	3.47	220	190	190
Wall_200	5.56	262	233	233

Table C1 (*continued*)

Investment choice[1]	R_value[2], $K{*}m^2/W$	Cost of ECMs for SFDs, €/m^2	Cost of ECMs for MFDs, €/m^2	Cost of ECMs for NRBs, €/m^2
Wall_250	6.94	298	269	269
Roof_145	3.45	34	31	31
Roof_245	5.83	43	40	40
Roof_345	8.21	54	51	51
Window_12	0.83	577	520	491
Window_11	0.91	612	546	517
Window_08	1.25	720	652	606
VHR system	50%[3]	5,130[4]	Variable[5]	Variable[5]

[1] The same set of ECMs is available as investment choices in each investment period (modeled year).
[2] The R_value is the thermal resistance and mathematically is the reciprocal of the U-value, i.e., $U = 1/R$. For roofs and walls, the R_value indicates thermal resistance, which is added to the reference thermal resistance of a building envelope component if an ECM is implemented. For windows, the R_value indicates the new thermal resistance of exchanged windows.
[3] Efficiency of the VHR system.
[4] The cost of the VHR system for SFDs consists of the investment cost of 5,130 €/house plus the yearly running cost of 100 €/year [39].
[5] The cost of the VHR systems for MFDs and NRBs consist of the investment cost, which is calculated as follows: *Fixed_cost + Vc·Afloor·Fixed_rate*, where *Fixed_cost* is a fixed installation cost per building (12,000 €/building [39]),*Vc* is the ventilation flow rate of a building ($m^3/s{\cdot}m^2$), *Afloor* is the heated floor area of a building (m^2), and *Fixed_rate* is the fixed investment rate per unit of ventilated air (6500 €/m^3/s [39]), plus the yearly running cost of 100 €/year [39].

Table C2
Technical parameters of the heat generation technologies included in the present work as investment choices in the DH system of Gothenburg. The efficiencies of the heat-only boilers (HOBs) and combined heat and power (CHP) generation units are based on the lower heating value of the fuel (a flue gas condensation technology is used) and, therefore, have values higher than 100%. Most of the data are obtained from the Danish Energy Agency [27], unless otherwise indicated in a footnote.

Investment choice[1]	Minimal output[2], %	Efficiency at rated capacity output, %	Efficiency at minimal output, %	Power-to-heat ratio	Load factor	Lifetime
HP sewage	10	0.6[3]	0.4[3]	–	0.99	25
HP air	10	0.6[3]	0.4[3]	–	0.99	25
Electric boiler	5	99	95	–	0.99	20
HOB wood chips	20	112	101.2[4]	–	0.97	25
Solar heating	0	48	48	–	1	30
CHP wood chips	45	112	101.2[4]	0.36	0.97	25

[1] The same set of heat generation technologies is available as investment choices in each investment period (modeled year).
[2] Minimal output level of a generation unit, expressed as a percentage of the rated (installed) capacity.
[3] Values reflect decreases in the theoretical COP value for HPs due to mechanical and thermal losses.
[4] Efficiency at minimal output is assumed to decrease by 10% compared to the efficiency at rated capacity output (based on the values indicated in [40] for HOBs and in [41] for CHP plants).

Table C3
Assumed costs and taxes for the heat generation technologies included in the present work as investment choices in the DH system of Gothenburg. The majority of the data are obtained from the Danish Energy Agency [27], unless noted otherwise in a footnote. The values are applicable to all the modeled years (2020–2050) unless specified otherwise.

Investment option	Fuel cost, €/MWh_{fuel}	Variable cost, €/MWh_{heat}	Energy tax, €/MWh_{input}	Start-up cost[3], €/MW_{output}	Investment cost[4], k€/MW_{heat}	Fixed cost[7], k€/MW_{heat}/year
HP sewage	electricity price	1.7	29[2]	–	590	2
HP air	electricity price	1.7	29[2]	–	590	2
Electric boiler	electricity price	0.5	29[2]	–	60	1
HOB wood chips	21[1]	1	–	36.7	750	31.2
Solar heating	–	–	–	–	0.18[5]	–
CHP wood chips	21[1]	1.34	–	170.1	32,006	92.3[6]

[1] Indicated value is assumed for Year 2020, which is based on the values provided by the DH system operator for Year 2012. For Years 2030, 2040, and 2050, the biomass prices are 40, 45, and 50 €/MWh, respectively (extracted from the study of Hagberg et al. [42] from the modeled case #30).
[2] Energy tax is levied on the consumption of electricity in Sweden.
[3] The values for start-up cost are expressed in €/MW of increased output due to the specifics of the two-variable approach applied in this work to govern the start-up and part-load operational characteristics of the heat generation units. It is assumed that HOBs can be started up within an hour, so the start-up cost for HOBs is assumed to be equal to the sum of the fuel and variable costs divided by the efficiency at rated capacity. The start-up cost for the modeled biomass-fired CHP plants is based on the total start-up cost of the existing biomass-fired CHP unit in the DH system of Gothenburg.
[4] The values for HPs, HOBs, and CHP plants in Year 2050 are reduced by 10%, as compared to the preceding years (according to [27]).
[5] The value is in k€/m^2 of installed solar collectors.
[6] The value is in k€/MW_{el} of installed CHP plant capacity.
[7] The values for HOBs and CHP plants in Year 2050 are reduced by 6%, as compared to the preceding years (according to [27]).

Table C4
Assumed technical and economic data for the thermal energy storage (TES) types included in the present work as investment choices in the DH system of Gothenburg.

Investment choice[1]	C-factor[2]	Charging efficiency[3], %	Discharging efficiency[3], %	Variable losses[4], %	Constant losses[5], %	Investment cost[6], €/MWh	Lifetime
Tank TES	1/6	98	98	1/240	4.3/240	11,100	25
Pit TES	1/210	98	98	1/240	4.3/240	422	25
Borehole TES	1/3000	98	98	1/240	4.3/240	1140	25

[1] The same set of TES types is available as investment choices in each investment period (modeled year).
[2] The C-factor governs the charge and discharge rates of a TES as follows: *charge (discharge) rate* $\leq TES_{capacity}$**C-factor*. The C-factors for the Tank TES and Borehole TES types are extracted from the study of P. Holmer and J. Ullmark [43]. The C-factor for the Pit TES is calculated based on information for the Sunstore 3 Dronninglund Plant in Denmark [44].
[3] The charge and discharge efficiencies are obtained from elsewhere [45];
[4] The hourly variable energy losses are related to the state of charge of a TES. For the Tank TES, variable losses are verified against the utilization records of a large-scale tank TES installed in one of the Swedish DH systems. Variable losses for the Pit TES and Borehole TES are assumed to be the same as those for the Tank TES.
[5] The constant hourly losses are related to the size of a TES and correspond to the losses from TES that occur even at zero-energy level (at zero-energy level, the water temperature inside a TES is still at the same level as the return water temperature in the DH network, and therefore higher than the surrounding ground/air temperature). Thus, constant losses occur even if a TES is "empty", i.e., no thermal energy is available for discharging). The constant hourly losses are derived from the study of P. Holmer and J. Ullmark [43].
[6] The values for the Tank TES and Borehole TES types are extracted from the study of A.R. Espagnet [46], the value for the Pit TES is calculated based on the information for the Sunstore 3 Dronninglund Plant, Denmark [44].

Appendix D

Fig. D1.

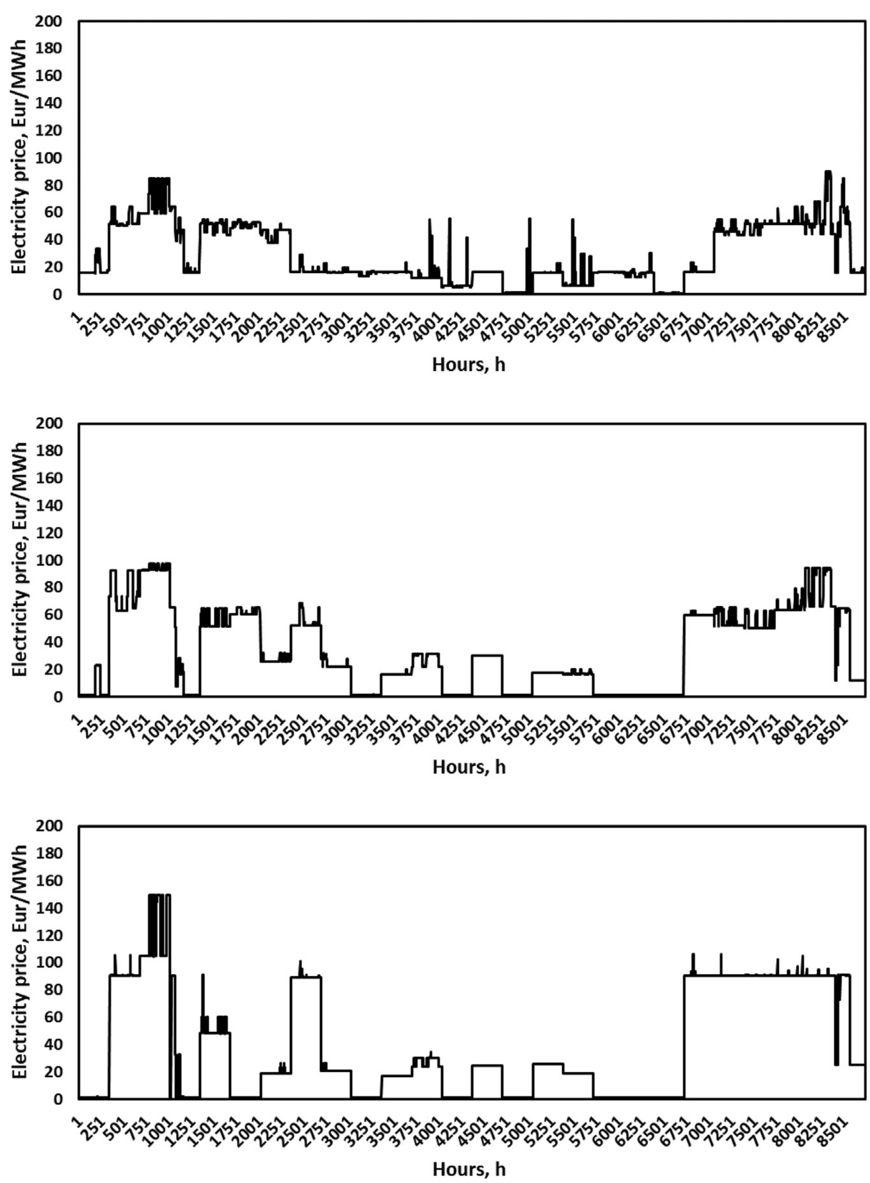

Fig. D1. Electricity price profiles derived from the ELIN/EPOD modeling package and applied in the present work for Years 2030 (a), 2040 (b), and 2050 (c) (the first hour of each profile corresponds to the first hour on January 1st). The profiles span 8,735 h (as compared to 8,760 h in reality) due to the features of the modeling approach.

References

[1] European Commission, Evaluation of the Energy Performance of Buildings Directive 2010/31/EU, 2015.
[2] European Commission, DIRECTIVE (EU) 2018/844 of the European Parlament and of the Council amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, 30.06.2018.
[3] Swedish Energy Agency, Energy in Sweden 2018 - An Overview, Swedish Energy Agency, 2018.
[4] Ministry of Sustainable Development of Sweden, National programme for energy efficiency and energy-smart construction, Stockholm, 2006.
[5] Ministry of Environment and Energy, Sweden's draft integrated national energy and climate plan, 2018.
[6] Survey on the energy needs and architectural features of the EU building stock, iNSPiRE System energy renovation of buildings, 2014.
[7] I. Ballarini, S.P. Corgnati, V. Corrado, Use of reference buildings to assess the energy saving potentials of the residential building stock: the experience of TABULA project, Energy Policy 68 (2014) 273–284.
[8] E. Mata, A.S. Kalagasidis, F. Johnsson, Energy usage and technical potential for energy saving measures in the Swedish residential building stock, Energy Policy 55 (2013) 404–414.
[9] H. Tommerup, S. Svendsen, Energy savings in Danish residential building stock, Energy Build. 38 (6) (2006) 618–626.
[10] Y. Liu, T. Liu, S. Ye, Y. Liu, Cost-benefit analysis for Energy Efficiency Retrofit of existing buildings: a case study in China, J. Cleaner Prod. 177 (2018) 493–506.
[11] A. Dodoo, L. Gustavsson, U.Y. Tettey, Final energy savings and cost-effectiveness of deep energy renovation of a multi-storey residential building, Energy 135 (2017) 563–576.
[12] S. Werner, District heating and cooling in Sweden, Energy 126 (2017) 419–429.
[13] International Energy Agency, Energy Technology Perspective 2016 - Towards Sustainable Urban Energy Systems, International Energy Agency, Paris, 2016.
[14] K. Difs, M. Bennstam, L. Trygg, L. Nordenstam, Energy conservation measures in buildings heated by district heating – a local energy system perspective, Energy 35 (2010) 3194–3203.
[15] S. Blomqvist, L.L. Fleur, S. Amiri, P. Rohdin, L. Ödlund, The impact on system performance when renovating a multifamily building stock in a district heated region, Sustainability 11 (2019) 1–18.
[16] L. Gustavssona, A. Dodoo, N. Truong, I. Danielski, Primary energy implications of end-use energy efficiency measures in district heated buildings, Energy Build. 43 (2011) 38–48.
[17] T. Lidberg, T. Olofsson, L. Trygg, System impact of energy efficient building refurbishment within a district heated region, Energy 106 (2016) 45–53.
[18] L. Lundström, F. Wallin, Heat demand profiles of energy conservation measures in buildings and their impact on a district heating system, Appl. Energy 161 (2016) 290299.
[19] K. Sperling, B. Möller, End-use energy savings and district heating expansion in a local renewable energy system – a short-term perspective, Appl. Energy 92 (2012) 831–842.
[20] C. Delmastro, F. Martinsson, J. Dulac, S. Corgnati, Sustainable urban heat strategies: perspectives from integrated district energy choices and energy conservation in buildings. Case studies in Torino and Stockholm, Energy 138 (2017) 1209–1220.
[21] D. Romanchenko, E. Nyholm, M. Odenberger, F. Johnsson, flexibility potential of space heating demand response in buildings for district heating systems, Energies 12 (2019).
[22] C. Weber, Uncertainty in the Electric Power Industry: Methods and Models for Decision Support, Springer-Verlag, New York, New York, 2005.
[23] L. Göransson, The Impact of Wind Power Variability on the Least-cost Dispatch of Units in the Electricity Generation System, Chalmers Reproservice, Gothenburg, 2014.
[24] The National Board of Housing, Building and Planning, Teknisk status i den svenska bebyggelsen - resultat från projektet BETSI, Boverket, 2010.
[25] Boverket - National Board of Housing, Building and Planning, "www.boverket.se," Boverket, [Online]. Available: <https://www.boverket.se/en/start-in-english/>. (accessed 24 01 2018])
[26] Statistics Sweden (SCB), <http://www.scb.se/>, Statistiska centralbyrån,. [Online]. (ccessed 06 11 2017).
[27] D.E. Agency, Technology Data for Energy Plants for Electricity and District heating generation, Danish Energy Agency, Copenhagen, 2016.
[28] M. Gustafsson, Energy Efficient Renovation Strategies for Swedish and Other European Residential and Office Buildings, KTH Royal Institute of Technology, Stockholm, 2017.
[29] Socialstyrelsen, "Temperatur inomhus," Bergslagens Grafiska, Lindesberg, 2005.
[30] L. Ekberg, Revised Swedish Guidelines for the Specification of Indoor Climate Requirements released by SWEDVAC, Proceedings of Clima 2007 WellBeing Indoors, 2007.
[31] S. Langer, G. Bekö, Indoor air quality in the Swedish housing stock and its dependence on building characteristics, Build. Environ. 69 (November 2013) 44–54.
[32] SMHI - Swedish Meteorological and Hydrological Institute, <http://strang.smhi.se/>, [Online]. Available:<http://strang.smhi.se/extraction/index.php> (accessed 24 11 2017).
[33] Nord Pool, <http://www.nordpoolspot.com/>," [Online]. Available: <http://www.nordpoolspot.com/historical-market-data/>.
[34] M. Odenberger, T. Unger, F. Johnsson, Pathways for the North European electricity supply, Energy Policy 37 (5) (2009) 1660–1677.
[35] L. Göransson, J. Goop, T. Unger, M. Odenberger, F. Johnsson, Linkages between demand-side management and congestion in the European electricity transmission system, Energy 69 (2014) 860–872.
[36] Energimyndigheten, "Energy in Sweden - facts and figures 2012," Energimyndigheten, 2012.
[37] Nordenergi WG Taxes and Levies, "Nordic Tax Report 2013 - Electricity sector," 2014.
[38] E. Nyholm, The role of Swedish single-family dwellings in the electricity system- The importance and impacts of solar photovoltaics, demand response, and energy storage, Gothenburg, Sweden, 2016.
[39] Boverket, "Energi i Bebyggelsen—Tekniska Egenskaper Och Beräkningar—Resultat Från Projektet BETSI," Boverket, Karlskrona, Sweden, 2010.
[40] F. Mermoud, A. Haroutunian, J. Faessler, B. Lachal, Impact of load variations on wood boiler efficiency and emissions, Arch. Sci. 68 (2015) 27–38.
[41] H. Wang, W. Yin, E. Abdollahi, R. Lahdelma, W. Jiao, Modelling and optimization of CHP based district heating system with renewable energy production and energy storage, Appl. Energy 159 (2015) 401–421.
[42] M.B. Hagberg, K. Pettersson, E.O. Ahlgren, Bioenergy futures in Sweden - modeling integration scenarios for biofuel production, Energy 109 (2016) 1026–1039.
[43] P. Holmer, J. Ullmark, "he potential of heat storage as variation management in the electricity and district heating sectors, Gothenburg, 2018.
[44] Global Solar Thermal Energy Council; <www.solarthermalworld.org>, [Online]. Available: <https://www.solarthermalworld.org/news/seasonal-pit-heat-storage-cost-benchmark-30-eurm3>. (accessed 28 10 2019)
[45] D. Romanchenko, J. Kensby, M. Odenberger, F. Johnsson, Thermal energy storage in district heating: centralised storage vs. storage in thermal inertia of buildings, Energy and Buildings (2017).
[46] A.R. Espagnet, Techno-Economic Assessment of Thermal Emergy Storage integration into Low Temperature District Heating Network, Stockholm, 2016.