

Cost-effective renovation of Nordic old apartment heating systems with hydrogen-production-based low-temperature district heating

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ABSTRACT

Integrating waste heat from hydrogen production into low-temperature district heating (LTDH) can improve hydrogen production profitability and the renewable energy usage of building heating. However, cost-effectiveness evidence for such applications on the demand side of old buildings remains limited. This study evaluates the potential of hydrogen-production-based waste heat in an LTDH context for two old Finnish apartment buildings with commonly used high-temperature radiators (80/50 °C and 70/40 °C). Based on these buildings, LTDH solutions are proposed to address the temperature mismatch between LTDH supply and existing space heating systems: retaining the existing radiators with the backup heater (an electric heater or a heat pump), and retrofitting low-temperature radiators (60/30 °C) compatible with LTDH. IDA ICE was used for energy simulations for representative weather years and a future climate scenario of 2050, and indoor temperature simulation during the cold event. The economic feasibility of each solution is evaluated. The findings indicate that LTDH meets at least 93% of total heat demand with 80/50 °C radiators and about 99% with 70/40 °C radiators. Backup electric heaters and heat pumps raise peak electricity demand by up to 169% and 38%, respectively, relative to the references. Resilience analysis indicates that backup heating is required to maintain indoor temperatures for the old building with 80/50 °C radiators. Economically, all proposed LTDH solutions are feasible with lower life-cycle costs (LCC) than the reference cases. Electric heater yields the shortest discounted payback period, whereas the heat pump solution offers the lowest cost over the full life cycle.

1. Introduction

To address the challenge of global climate change, the European Union has advanced an ambitious European Green Deal that raises the emissions reduction target to 55% by 2030, and 90% reduction is proposed for 2040 [1]. The building sector, as the largest single energy consumer, is responsible for 40% of final energy use and 36% of greenhouse gas emissions of EU. Of which approximately 80% consumption is associated with space heating, cooling, and domestic hot water (DHW) production in the residential sector [2]. Consequently, integrating sustainable energy systems for buildings is critical in the context of decarbonization.

District heating systems (DH) are widely adopted as an efficient centralized heating solution in Nordic and Central European countries. In Finland, DH is the primary space heating solution, supplied around 45% of space heating demand in 2022 [3]. By 2024, renewable energy, waste heat recovery, and electric boilers accounted for 73% of Finland's

district heat production [3]. Nevertheless, further integration of renewable and sustainable energy sources into district heating networks remains crucial to achieve deeper decarbonization and reduce dependence on fossil fuels.

A promising approach to achieving sustainable DH is utilizing low-temperature district heating (LTDH). Low-temperature district heating refers to district heating with a supply water temperature below 70 °C [4,5]. Compared with conventional high-temperature DH (HTDH), LTDH shows its advantages in saving transmission heat losses, and distribution losses, increasing overall efficiency, and improving the efficiency of low-temperature production units such as waste heat and renewable energy sources [6]. Moreover, the application of LTDH enhances the feasibility of integrating thermal energy storage systems.

The technical feasibility of LTDH in residential buildings has been investigated in both field studies and simulations. [7] implemented LTDH in 18 existing detached houses in Denmark, operating with DH supply temperatures as low as 45 °C for most hours of the year. The

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houses retained their existing hydronic radiators, and electric heaters were used to support DHW production. The result reported acceptable thermal comfort without occupants' complaints under LTDH operation. [8] conducted numerical simulations for a Norwegian terraced house with high-temperature radiators and found that indoor comfort could be maintained with a 50 °C DH supply during about 80% of the year, while the remaining hours could be met by increasing the supply water mass flow or utilizing a 60 °C supply.

A major barrier to large-scale LTDH deployment is compatibility with the existing building stock, especially apartments constructed between 1960 and 1970, which account for roughly 40% of the current apartment stock in Finland [9]. These old apartments usually rely on heating systems designed for conventional high-temperature DH and therefore can hardly be directly supplied by LTDH. Therefore, additional auxiliary heat sources may be required for the building to raise hot water temperatures for space heating and DHW production. Thorsen & Ommen [10] proposed a heat booster substation that combines a heat pump with LTDH, using a 45 °C network as both the heat pump source and a supply for domestic hot water production. The solution delivered is found capable of supplying 55 °C DHW, while the storage tank covered the occupants' demand with considerable energy saving potential. Masip et al. [11] tested the performance of three LTDH solutions for DHW production in Valencia using numerical simulation, including gas boiler, immersion electric heater, and ultra-low temperature district heating. The results indicate that the heat pump combined with LTDH saved over 0.3 GWh of energy usage per year, equivalent to about 70% of the conventional system. Knudsen & Petersen [12] further presented a model predictive control strategy for an LTDH and heat pump hybrid system under demand response, achieving up to 15% annual energy savings relative to a conventional heat pump system.

Despite the widely discussed energy saving potential of LTDH solutions, their cost-effectiveness has received much less attention. The limited economic analyses mainly focus on the perspective of energy producers or DH operators[13,14]. There remains a clear gap in studies that evaluate economic feasibility from the viewpoint of building owners, particularly for existing old apartment buildings. Considering the significant investment cost of related systems and the additional limitations and expenses associated with building retrofit, such evaluations are essential for wider adoption of LTDH in the existing apartment stock.

On the other hand, LTDH promotes the integration of low-temperature waste heat sources, such as waste heat from hydrogen production. Hydrogen is considered one of the most promising clean energy sources that offers a low-carbon and environmentally friendly option for sustainable energy production [15]. Current hydrogen production approaches are hindered by inefficiencies, with substantial industrial waste heat generation, around 10 to 20 MWh per ton of hydrogen produced [16]. If not appropriately managed, this waste heat might reduce overall production efficiency and contributes to thermal pollution. This issue can be addressed by integrating hydrogen production waste heat into LTDH, which improves both hydrogen system efficiency and the renewable integration within DH.

Several studies have explored the potential for using hydrogen-production-based waste heat in DH systems. In the United Kingdom, Burrin et al. [17] assessed the waste heat recovery from a combined heat and hydrogen (CHH) plant for a DH network and reported a heat recovery potential of about 312 kW per 1 MW of electric consumption, equivalent to roughly 60% of demand in a small-scale local DH network. In the Netherlands, van der Roest et al. [18] investigated waste heat recovery from an electrolyser powered by local photovoltaic generation and low-cost grid electricity, increasing overall energy efficiency from 76% to 91% with recovered heat meeting 16% of the total community heating demand. In Finland, Meriläinen et al. [19] evaluated the waste heat potential of off-grid alkaline electrolysis for the DH network. The results show that by 2040, the available waste heat could supply the whole national DH demand. Although existing works demonstrate

technical potential, they mainly focus on the supply side technology and energy potential, with limited evidence on economic feasibility at the building level. In particular, the economic benefits of applying hydrogen-production-based waste heat LTDH in specific buildings remain underexplored, which is critical for its practical deployment.

In summary, although the energy performance of LTDH has been investigated widely, there is a research gap on the economic feasibility of LTDH solutions for existing old apartment buildings from the building owners' point of view. Moreover, studies on integrating hydrogen-production-based waste heat into DH largely emphasize supply-side potential and seldom assess its economic performance on the building side. Addressing these gaps, this study evaluates the energy performance and economic feasibility of hydrogen-production-based waste heat LTDH solutions for old apartment buildings in Nordic climates. The analysis considers multiple weather year scenarios and compares several LTDH configurations. A key novelty of this study is the inclusion of hydrogen-production-based waste heat LTDH in the assessment, which enables a direct evaluation of its economic viability at the building level. An additional contribution is the evaluation of the proposed LTDH solutions under the expected future climate scenario, which supports an assessment of long-term technical potential.

2. Methodology

2.1. Framework of the study

This study aims to investigate the feasibility of applying hydrogen-production-based waste heat LTDH in old apartment buildings. To address the temperature mismatch between LTDH and conventional high-temperature radiator systems, several solutions were proposed. Energy simulations and indoor temperature simulations by IDA ICE as well as economic calculations were conducted to evaluate the energy performance, resiliency and cost-effectiveness of the proposed solutions. The overall research framework is illustrated in Fig. 1.

As shown in Fig. 1, the study first developed the building models in

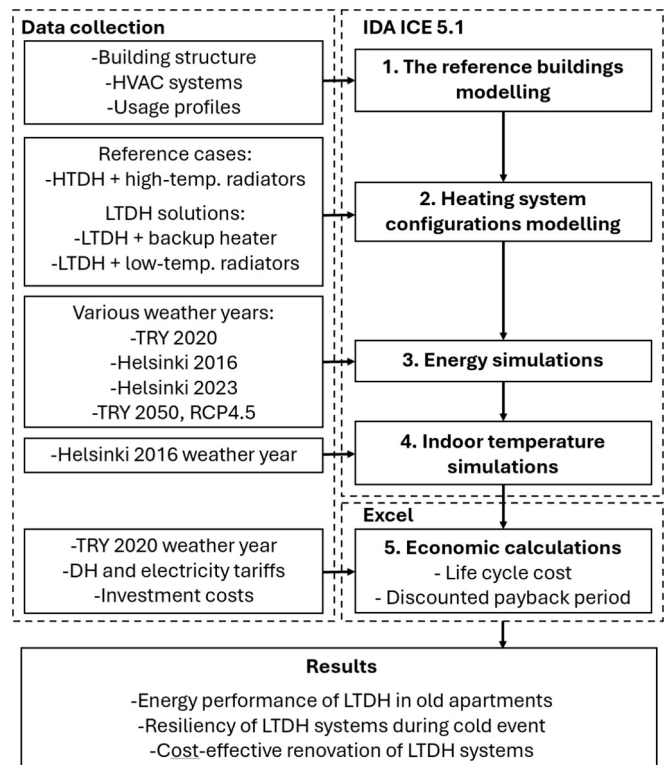


Fig. 1. Framework of the research.

the IDA ICE environment based on collected data, as described in Section 2.3. In the second step, the heating system configurations of the studied cases were modeled using the IDA ICE ESBO plant module. These cases included a conventional high-temperature district heating system with high-temperature radiators as the reference and several alternative LTDH-based solutions. In the third step, indoor temperature and energy simulations were performed under various weather datasets to assess the resiliency and energy performance of the cases. Based on the simulation results, economic calculations were carried out, including life-cycle cost (LCC) and discounted payback period. As a result, the energy performance and cost-effectiveness of the proposed solutions were evaluated, the cost-optimal LTDH solution for old apartment buildings was identified by comparison analysis.

2.2. The studied buildings

Two similar old apartment buildings were investigated in this study. They were both structured in 1969, located in Helsinki, Finland. They share the same layouts, structure, thermal insulation and similar HVAC systems. Each building consists of 5 floors, including apartments, a sauna room, a laundry room, technical space and basements. The total heated floor area of each building is 4994 m², served by a radiator network connected to the district heating system. The only difference between the two buildings lies in the design temperature levels of their radiator systems, which are described in Section 2.2.3. There is no mechanical cooling employed in the studied buildings.

2.2.1. Location and weather

Based on the Finnish national building code [20], Finland is classified into 4 climate zones, which are used for the building heating power and energy consumption calculation. Helsinki is located in climate zone I, with a reference ambient temperature for heating system dimensioning of -26 °C.

In this study, the Test Reference Year 2020 (TRY2020) dataset was adopted as the average weather scenario for both energy simulations

and economic analysis. This dataset describes 30-years average weather conditions in southern Finland based on observations from 1989 to 2018. It provides hourly data on temperature, relative humidity, solar radiation, wind speed and direction designed to represent the average weather conditions of Finnish Climate Zone I [21,22].

In addition to TRY2020, several other weather datasets were employed for energy simulations. The measured weather data from the closest weather station in Helsinki for the years 2016 was selected as the cold weather scenario, given the low minimal outdoor temperature and long cold periods below -20 °C. The measured weather data from the same weather station for the year 2023 was selected as the warm weather scenario since its relatively high outdoor temperature. Moreover, a future scenario was also considered by using the estimated test reference year 2050 weather dataset. It is generated by combining the weather observations selected for TRY2020 with multi-model mean climate change projections for our study region, presenting the future climate in the middle of this century under moderate climate change [21,22].

Fig. 2 illustrate the hourly outdoor temperatures for all datasets used in this study, while Table 1 summarizes the properties for the selected years.

Table 1
Properties of the selected years.

Years	Min. temperature [°C]	Heating degree days [Kd]	Hours below -20 °C [h]
TRY 2020	-24.9	3788	23
Year 2016	-25.0	3589	64
Year 2023	-15.0	3493	0
TRY 2050	-20.5	3221	1

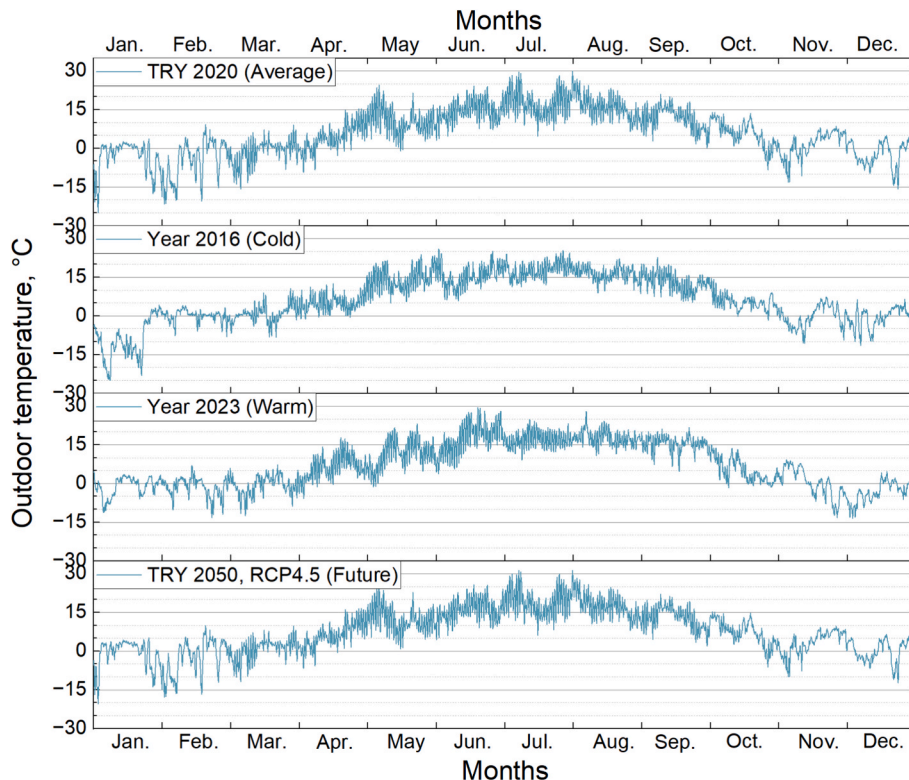


Fig. 2. Hourly outdoor temperature of selected years.

2.2.2. Geometry and structure

The two studied buildings share an identical architectural layout. Each building has an overall height of 13 m, a width of 96 m, and a depth of 11 m. Each building has 5 floors, including an underground level. A total of 48 apartments are distributed across the aboveground floors of each building. They are arranged into six units connected by six staircases. The system infrastructures such as DH substation are installed in technical space located in basement. Besides, in each building, there are a sauna room and a laundry room on the underground level. Fig. 3 illustrates the outlook of the studied apartment buildings and a unit floor plan located at the building corner.

Table 2 shows the main structure of the studied buildings. Both studied buildings are structured with reinforced concrete. The windows of the buildings have been renovated, while no other energy renovations have been made to the buildings' envelope.

2.2.3. Reference HVAC systems

Both studied buildings are heated by radiator heat distribution systems connected to a conventional district heating network, with different designed radiator temperature levels for different buildings. Specifically, building A is equipped with radiators designed for inlet/outlet water temperatures of 80/50 °C, while the building B uses 70/40 °C radiators. These temperature levels are commonly used for old apartment buildings in Finland. Fig. 4 presents the radiator inlet water temperature control curves as a function of outdoor temperature.

Moreover, mechanical exhaust ventilation systems without heat recovery were applied in both studied buildings. The normal air change rate is 0.5 ACH, with an additional 30% increase in the morning and evening. Table 3 summarizes the main properties of the reference HVAC systems of the studied buildings. Fig. 5 presents the hourly domestic hot water usage profile created based on measurement consumption profile.

2.2.4. Internal heat gains

Table 4 summarizes the internal heat gains employed in this study. The values were selected based on measurements and are consistent with the Finnish building code D5 [20]. Detailed hourly internal heat gain profiles were used for dynamic energy simulations, representing the behavior of occupants in Finnish old apartment buildings.

2.2.5. District heating

In this study, conventional high-temperature district heating (HTDH) was investigated as a reference heat source. The supply temperature of this system varies between 75 °C and 90 °C, depending on the outdoor air temperature, which enables direct heating of high-temperature radiators as well as domestic hot water production.

In addition to the conventional system, a LTDH system based on waste heat from an off-grid alkaline water electrolyzer plant was also

Table 2 Properties of the studied buildings.

Structures	Value	Others
External walls, U-value [W/m ² K]	0.48	
Roof, U-value [W/m ² K]	0.47	
Floor slab (toward grounds), U-value [W/m ² K]	0.47	
External doors, U-value [W/m ² K]	2.2	
Windows, U-value [W/m ² K]	1.0	g-value: 0.36 ST-value: 0.33 Frame depth: 180 mm
Integrated window shading	Blinds between panes	Multiplier for g-value: 0.33 Multiplier for T-value: 0.12 Multiplier for U-value: 0.95
Air leakage rate at 50 Pa pressure difference (n ₅₀), ACH	3	

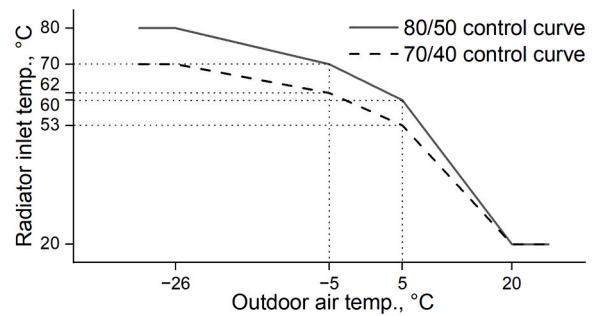


Fig. 4. Control curves of radiator inlet water temperature according to outdoor temperature.

studied. This system represents a 100% renewable energy source, as the waste heat is gathered from electrolysis plants powered by wind and solar energy. The process is described in detail by Meriläinen et al. [23]. The supply temperature of this system is constant at 65 °C. The supply temperature with different outdoor air temperatures for the two district heating systems are illustrated in Fig. 6.

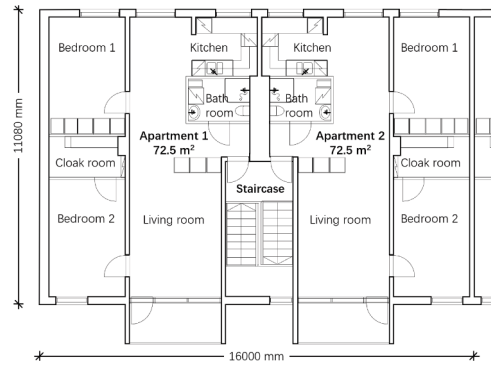
2.3. Simulation set-up

2.3.1. Simulation tool

In this study, the energy simulations were carried out using IDA Indoor Climate and Energy (IDA ICE) version 5.1, developed by EQUA Simulation AB. The software is capable of performing multi-zone



(a) Photo of the studied apartment buildings



(b) Layout of the corner apartment unit

Fig. 3. Photo and layout of studied apartment buildings.

Table 3
Properties of the reference HVAC system of the studied buildings.

Ventilation systems	
Ventilation system type	Mechanical exhaust ventilation system
Total exhaust air flow rate [m ³ /s]	1.7
Heat recovery	None
Heating systems	
Heating carrier	District heating
Heating capacity of district heating	303 kW for space heating, 65 kW for domestic hot water
The dimensioning conditions of district heating [°C]	-26
Heating setpoint temperature [°C]	21 for apartment rooms, 22 for laundry, and 17 for common areas (staircases and the cellar)
Space heating room units	Water radiators
Dimensioning temp. of the space heating [°C / °C]	80/50 or 70/40 for demo building A and B, respectively
DHW temperature setpoint [°C]	58
Annual hot water usage [kWh/m ²]	65.2

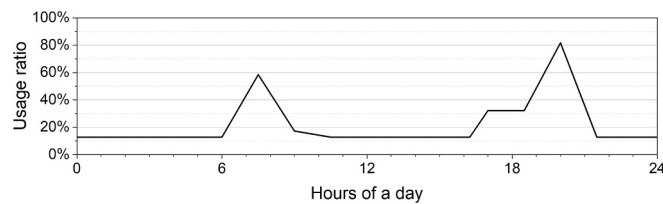


Fig. 5. Domestic hot water usage schedule used in simulations.

Table 4
Internal heat gains used in simulations.

Internal heat gains	
Occupants	88 occupants in total, occupancy density 0.024 no./m ² (only in apartments) with activity level of 1.2 MET, clothing level of 0.85 ± 0.25 CLO.
Lighting	Average heat gains 2.4 W/m ² , internal gain from lighting 6.1 kWh/m ² , a.
Equipment	Average heat gains 4.6 W/m ² , internal gain from equipment 19.5 kWh/m ² , a.

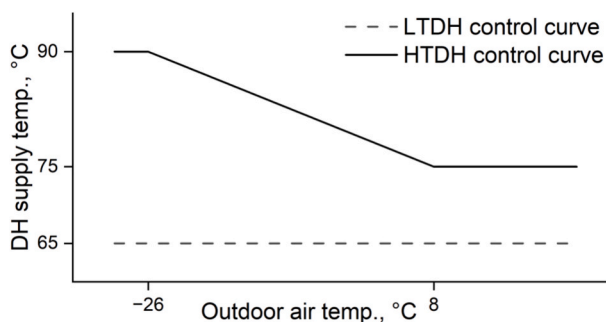


Fig. 6. Supply temperature of studied district heating variation according to outdoor temperature.

dynamic simulations of thermal comfort, indoor climate, and energy consumption. With the ESBO module, IDA ICE enables detailed modeling of HVAC systems, including high- and low-temperature district heating as well as the different backup heating solutions investigated in this research[24]. The thermal behavior of heat exchangers and other system components is represented through embedded physical equations[24]. IDA ICE has been validated through standardized benchmark procedures defined in ASHRAE Standard 140[25].

Moreover, it has been further validated in several peer-reviewed studies through comparisons with measured building energy data, particularly under Nordic climate conditions [26–31].

2.3.2. Studied heating system configuration

A key challenge in applying LTDH to old apartment buildings is its incompatibility with the high-temperature radiator systems commonly used in old apartment buildings. In this study, the hydrogen-production-based LTDH system operates at a constant supply temperature of 65 °C, which is sufficient for domestic hot water, as Finnish regulation[32] requires at least 55 °C tap water. However, the design inlet temperatures of the investigated high-temperature radiator systems are 70 °C and 80 °C, which cannot be directly achieved with LTDH.

To address this challenge, two strategies were proposed:

- i) retaining the existing high-temperature radiators and adding backup heating, such as electric heater or heat pump; or.
- ii) replacing the high-temperature radiators with low-temperature radiators (LTR, 60/30 °C) compatible with LTDH.

Accordingly, three LTDH configurations for the studied old apartment buildings were developed, differing in backup heating and radiator types. Moreover, a conventional high-temperature district heating system was simulated as a reference for comparison. All studied configurations are illustrated in Fig. 7.

Fig. 7(a) shows the conventional high-temperature district heating configuration commonly used in Finnish old apartment buildings. The district heating supply water is delivered directly to heat exchangers of the building, where the heat is transferred to the secondary loop of different heating subsystems of the buildings. This conventional configuration was used in reference cases combined with two different high-temperature radiator systems with designed temperatures of 80/50 °C and 70/40 °C. Fig. 7(b) presents the LTDH configuration with renovated low-temperature radiators. It shares similar principles with conventional configuration, except for the different temperature levels of district heating and radiator systems.

Fig. 7(c) and (d) illustrate the LTDH configuration with original high-temperature radiators and backup heaters. In Fig. 7(c), the district heating return water is directed directly to the heat exchangers, and any backup heating demand would be covered by the electric heater located after the exchanger.

Fig. 7(d) shows the configuration with a heat pump, in which the district heating would be used as a heat source driving the heat pump, where the water of the tank would be heated up to the required level and distributed through heat exchangers to space heating circuit. The tank setpoint is maintained at 5 °C above the setpoint of radiators to ensure efficient heat transfer.

In this study, the heat pump configuration was only applied to the studied building A with 80/50 °C radiators, as its use with 70/40 °C radiators would provide little practical benefit. The small temperature difference between the hydrogen-based LTDH supply (65 °C) and the target tank temperature (below 75 °C) would limit the heat pump's heating capacity, rendering the heat pump economically unfeasible.

The ESBO plant module of IDA ICE was used for detailed modeling of the demo buildings' heating system. Two separate heat exchangers were defined between the primary and secondary sides to evaluate the heating demands of domestic hot water and space heating. Each heat exchanger was equipped with a backup heating module, which allowed the backup heating demand in the studied district heating return water cases to be recorded. The district heating substation and related heating systems were dimensioned according to the Finnish National Building Code D5[20] to ensure sufficient capacity to meet the building's heating demand at the design outdoor temperature of -26 °C, excluding internal heat gains.

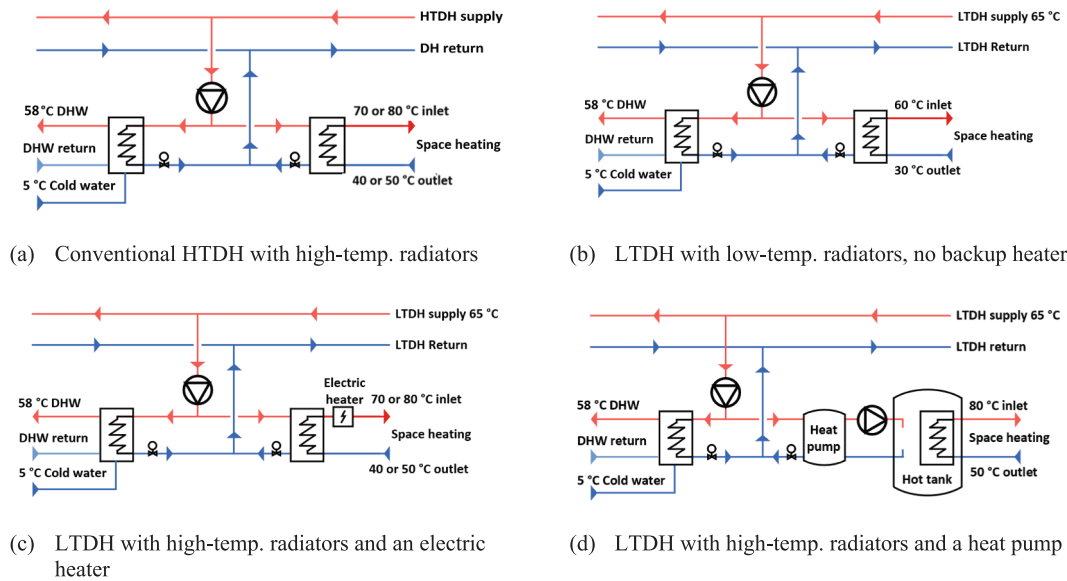


Fig. 7. Scheme of studied district heating configurations.

2.3.3. Heat pump electricity consumption calculation

The annual electricity consumption of the heat pump was calculated based on the hourly backup heating demand obtained from IDA ICE simulations and the corresponding coefficient of performance (COP) for each hour, as expressed as:

$$W_{HP} = \sum_1^{8760} \frac{q_{HP}(t)}{COP(t)} \tag{1}$$

where W_{HP} is the annual electricity consumption of the heat pump, kWh; $q_{HP}(t)$ is the hourly backup heating demand, kWh; $COP(t)$ is the hourly performance of coefficient of heat pump.

The hourly COP of the heat pump was determined using simulated hourly data. The COP was calculated using Equation (2), under the assumption of a constant loss factor[33]:

$$COP(t) = f_T(t) * COP_T(t) \tag{2}$$

where $f_T(t)$ is the loss factor of the compressor; $COP_T(t)$ is the theoretical hourly COP of the heat pump.

When at least one measured COP value of the heat pump is available, the compressor loss factor can be determined according to:

$$f_T(t) = \frac{COP_N}{COP_T} \tag{3}$$

where COP_N is the measured heat pump COP; COP_T is the theoretical heat pump COP.

The hourly theoretical COP is calculated with:

$$COP_T(t) = \frac{T_{HSy}}{T_{HSy} - T_{HS0}} \tag{4}$$

where T_{HSy} is the building heating system temperature, K; T_{HS0} is the heating source temperature, K.

In this study, the selected heat pump was provided by a local heat pump distributor [34]. Its loss factor was calculated as 0.219, corresponding to a COP of 7.29 under design conditions, where the evaporator inlet/outlet temperatures are 50/40 °C and the corresponding condenser temperatures are 30/60 °C. The LTDH system supplied a constant source temperature of 338.15 K, while the building heating system temperature was determined by the water tank setpoint. This setpoint was always maintained 5 K above the highest setpoint among the building subsystems and varied with the outdoor air temperature, with a maximum of 358.15 K. The heat pump was switched off when the

highest setpoint temperature the space heating fell below 338.15 K (65 °C), corresponding to a tank (see Fig. 7d) setpoint temperature below 343.15 K (70 °C). In such cases, the tank was directly heated by LTDH. This operational strategy reflects common control logic in practical heat pump applications.

2.3.4. Simulation cases

For the energy simulation, based on two studied reference buildings, seven simulation cases involving four different district heating configurations were defined for energy simulations, including two reference cases using HTDH system and five LTDH cases. The cases were grouped for comparative analysis, each against its respective reference case. All of the four investigated weather year datasets were involved in energy simulations (see section 2.2.1).

In reference cases, conventional high-temperature district heating was used as the sole heat source. In the remaining cases, hydrogen-production-based LTDH was applied as the primary heat source, combined either with low-temperature radiators (LTRs) or with high-temperature radiators supported by backup heating. The heat pump configuration was only applied in combination with 80/50 °C radiators. The detailed setup of all simulation cases is presented in Table 5.

Moreover, to examine the resiliency of LTDH solutions in old apartment buildings during cold events, eight indoor temperature simulation cases were defined for the two reference buildings. Each case was simulated for the coldest week of 2016 (January 4–11). No specific backup heating was included in these cases, as influence of the backup heating type on indoor temperature performance was considered minor. Detailed descriptions of the cases are provided in Table 6.

2.4. Calibration of building model

Hirvonen et al. [35] calibrated the IDA ICE model of reference buildings using measured data, focusing on heating and electricity consumption. The calibrated model represents the existing building conditions sole heated by conventional high-temperature district heating. Measured data were provided by the local energy provider with an accuracy of ± 3%.

The calibration parameters included the U-values of the retrofitted external walls and the domestic hot water (DHW) consumption (65 L/day/person). In addition, the usage schedules of lighting, equipments, and the sauna were calibrated based on measured hourly electricity consumption. The simulated monthly district heating consumption from

Table 5
Definitions of studied energy simulation cases.

Buildings	Ref. building A with 80/50 °C radiators				Ref. building B with 70/40 °C radiators		
	Heating systems	A-HTDH-80/50 (Ref.)	A-LTDH-80/50-EH	A-LTDH-80/50-HP	A-LTDH-60/30-LTR	B-HTDH-70/40 (Ref.)	B-LTDH-70/40-EH
Primary heating	Conventional HTDH	Hydrogen-production-based LTDH	Hydrogen-production-based LTDH	Hydrogen-production-based LTDH	Conventional HTDH	Hydrogen-production-based LTDH	Hydrogen-production-based LTDH
Backup heating	None	Electric heaters	Heat pump	None	None	Electric heaters	None
Radiator designed inlet/outlet temp. [°C/°C]	80/50	80/50	80/50	60/30	70/40	70/40	60/30

Table 6
Definitions of studied indoor temperature simulation cases.

Buildings	Ref. building A with 80/50 °C radiators				Ref. building B with 70/40 °C radiators			
	Heating systems	A-HTDH-80/50 (Ref.)	A-LTDH-80/50-BackUp	A-LTDH-80/50-NoBackUp	A-LTDH-80/50-NoBackUp-NoHG*	B-HTDH-70/40 (Ref.)	B-LTDH-70/40-BackUp	B-LTDH-70/40-NoBackUp
Primary heating	Conventional HTDH	Hydrogen-production-based LTDH	Hydrogen-production-based LTDH	Hydrogen-production-based LTDH	Conventional HTDH	Hydrogen-production-based LTDH	Hydrogen-production-based LTDH	Hydrogen-production-based LTDH
Backup heating	None	Yes	None	None	None	Yes	None	None
Heat gains	Yes	Yes	Yes	None	Yes	Yes	Yes	None
Radiator designed inlet/outlet temp. [°C/°C]	80/50	80/50	80/50	80/50	70/40	70/40	70/40	70/40

* In the naming of simulation cases, HG stands for heat gains.

the calibrated model was then compared with measurements, as shown in Fig. 8. The results indicate a great accuracy during whole simulation year, with an annual heating demand deviation of 5.9%.

2.5. Economic calculations

The economic analysis was carried out using the results of energy simulations in combination with dynamic electricity and district heating tariffs. The calculations were conducted based on TRY 2020 weather data, representing current average climatic conditions.

2.5.1. Life cycle cost and discounted payback period

The lifecycle cost (LCC) analysis was employed in this study to evaluate the cost-effectiveness of the investigated heating systems. The LCC was calculated as:

$$LCC_{25a} = \sum I_{O,tot} + \sum MR_a \times \frac{1 - (1+r)^{-n}}{r} + \sum R_M \times \frac{1}{(1+r)^{k_i}} + \sum E_a \times \frac{1 - (1+r_e)^{-n}}{r_e} - \sum Res_{tot} \quad (5)$$

where LCC_{25a} is the net present value (NPV) of the LCC of the studied system over a 25-year period, €; $\sum I_{O,tot}$ is the total investment cost of the renovation measures, €; MR_a is the annual maintenance and repair cost of the renovation measures, €/a; r is the real interest rate; n is the life-

cycle period considered in the analysis, 25 a; R_M is the renewal cost of the renovation measure, €; k_i the year in which the renewal is carried out; E_a is the annual energy cost, €/a; r_e is the escalated real interest rate; $\sum Res_{tot}$ is the total residual value of the renovation measures, €.

Escalated real interest rate is calculated by:

$$r_e = \frac{r - f_e}{1 + f_e} \quad (6)$$

where r is the real interest rate; f_e is the energy price escalation.

In the calculations, a discount period of 25 years was used. A real interest rate of 3% was applied to represent the time value of money, while an annual escalation rate of 2% was assumed for both electricity and district heating prices. The escalation rate reflects the historical average increase in Finnish energy prices and is consistent with assumptions used in previous studies [36,37].

Although LCC analysis provides comprehensive information on life-

cycle costs, it is less informative for investors when assessing the payback efficiency of the studied heating systems. Therefore, the discounted payback period was also applied in the economic analysis to indicate the time required to recover the initial investment. The discounted payback period was calculated as follows:

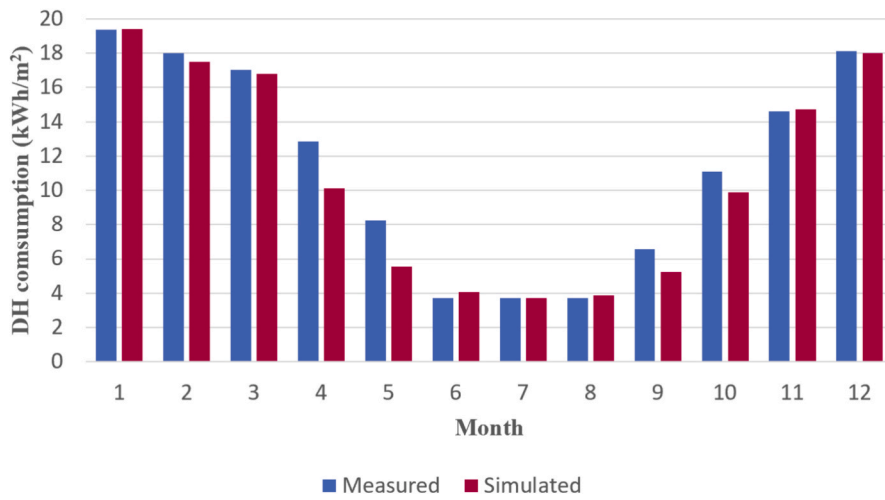


Fig. 8. Comparison of monthly measured and simulated district heating consumption. [35].

$$N_d = \frac{\ln 1 - \frac{\sum I_{O,tot} r_e}{A}}{\ln \frac{1}{1 + r_e}} \quad (7)$$

where N_d is the discounted payback period, a; A is the annual cash flow, €/a; $H_{HTDH,t}$ is the high-temperature district heating energy consumption of reference cases, MWh; $P_{HTDH,t}$ is the energy price of high-temperature district heating at time t , €/MWh; H_{hp} is the heating energy consumption from heat pump, MWh; COP is the coefficient of performance of the heat pump; E_{eh} is the electricity consumption from the electric heater, MWh;

$$A = \sum_{t=1}^{8760} \left[H_{HTDH,t} \times P_{HTDH,t} - \left(\frac{H_{hp}}{COP} + E_{eh} \right) \times P_{elec,t} - H_{LTDH,t} \times P_{LTDH,t} \right] + \Delta P_{bfdh} + \Delta P_{bfe} \quad (8)$$

Table 7
Investment costs of components of the studied district heating systems.

Cases	Component		Investment cost with 25.5% VAT, €	Others, €
HTDH (Ref.)	Electricity connection	50 A for the reference case	3643 [38]	
LTDH-EH	DH substation renovation		92,100 [27]	Residual value after 25 years: 60% of initial investment [27]
	Electric heaters	125 kW for 80/50 °C radiators	10,350 [37]	
		60 kW for 70/40 °C radiators	5300 [37]	
	Electricity connection**	230 A for building A with 80/50 °C radiators	10,350 [38]	
		160 A for building B with 70/40 °C radiators	9210 [38]	
LTDH-HP	Cables and substation for new electricity connection		19,060 [28]	
	DH substation renovation		92,100 [27]	Residual value after 25 years: 60% of initial investment
	HP	125 kW for 80/50 °C radiators	115,000 [37]	Maintenance: 0.75% of initial investment cost/a [28] Renewal cost: 26% of initial investment in 15th year [28]
				Residual value after 25 years: 50% of initial investment [27]
LTDH-60/30	Electricity connection	100 A for building A with 80/50 °C radiators	6073 [38]	
	Cables and substation for new electricity connection		19,060	
	DH substation renovation		92,100	Residual value after 25 years: 60% of initial investment
	Radiator renovation		214,740	Residual value after 25 years: 32.5% of initial investment [27]
	Electricity connection	50 A for both building A and B with 60/30 °C radiators	3643	
	Cables and substation for new electricity connection		19,060	

*Investment costs refer to prefabricated systems, including all relevant system components and installation work, such as: sensors and flow meters, check valves, pressure and temperature control valves, shut-off valves, controllers, and automation systems.

**The sizes of electricity connections were selected based on the simulated peak electricity demand under the dimensioning conditions of -26 °C, excluding internal heat gains.

Table 8
Energy tariffs for the studied buildings.

Energies	Price components	Price (25.5% VAT)
Electricity	Electricity energy price	Nordpool hourly price 2023, 71 €/MWh on average
	Electricity tax category I	28 €/MWh
	Electricity marginal fee	4.3 €/MWh
	Electricity transmission fee	21 €/MWh for 7 am–9 pm on winter workdays 11 €/MWh for other times
	Electricity fixed basic fee	39 €/ month
	Electricity power fee	5.7 €/kW.month, based on monthly peak power
District heating	DH energy price	Commercial HTDH Local monthly price 2023, 59 €/MWh on average Dynamic hourly price, 36 €/MWh on average [[23]]
	Hydrogen-production-based LTDH	
	DH power fee	6.3 €/kW.month, based on annual 3-hour peak power

$P_{elec,t}$ is the price of electricity at time t , €/MWh; $H_{LTDH,t}$ is the LTDH energy consumption of reference cases, MWh; $P_{LTDH,t}$ is the energy price of LTDH at time t , €/MWh; ΔP_{bfh} is the change in district heating basic fee, €/a; ΔP_{bfe} is the change in the electricity basic fee, €/a.

2.5.2. Investment cost

The investment costs and residual values of components for the studied district heating systems are detailed in Table 7. The investment cost of radiator renovation is provided by a local radiator contractor. The estimates refer to prefabricated systems for the studied apartment buildings, including all required equipment and installation work by qualified technical personnel, with a value-added tax of 25.5% applied in Finland. Given the high degree of case-specific customization, these values should not be directly scaled or generalized to other buildings or projects.

2.5.3. Energy tariffs

In this study, several electricity and district heating tariffs were considered in the economic analysis, including commercial electricity and district heating tariffs provided by a local company, as well as the hydrogen-production-based LTDH price proposed by Meriläinen et al. [19]. The latter represents the levelized cost of heat calculated using a 6% discount rate and was adopted as the LTDH tariff in this study, as no practical LTDH tariff data were available for the studied area. The components of the applied tariffs are listed in Table 8, and their hourly price distributions are shown in Fig. 9.

The annual electricity cost was calculated based on the simulated hourly electricity consumption of the entire building, including the HVAC facilities (e.g., circulation pumps), lighting, equipment. The total electricity costs consist of three components: (1) the energy cost, determined by hourly electricity consumption and consisting of the

dynamic energy price, electricity tax, marginal fee, and transmission fee; (2) a fixed basic fee; and (3) a power fee, charged monthly based on the peak electricity demand.

Similarly, the district heating costs consist of two components: (1) the energy cost, calculated from the hourly district heating demand and the applied energy price; and (2) a power fee, charged monthly based on the three-hour average peak power demand over the simulation year. For the district heating energy costs calculation, two energy tariffs were involved, for calculating the high-temperature and LTDH cost.

3. Results

3.1. Energy consumption analysis

3.1.1. Average weather scenario

Fig. 10 presents the simulated annual purchased energy of the studied buildings under the average weather scenario (TRY2020), including district heating and electricity consumption. The solid line indicates the ratio of the total heating demand covered by low-temperature district heating (LTDH). According to the result, for LTDH cases with original radiators supported by backup heating, LTDH was able to cover most of the building’s heating demand, with coverage ranging from 93.0% to 99.1% depending on the radiator temperature. The higher radiator temperature level resulted in lower LTDH coverage, as backup heating was required more frequently to reach the target radiator supply temperatures. For the cases with renovated low-temperature radiators (A-LTDH-60/30-LTR and B-LTDH-60/30-LTR), the building’s heating demand can be fully covered by the LTDH network.

Among all cases, the case with a heat pump (A-LTDH-80/50-HP) was the only one that significantly reduced total purchased energy. This is because of the high coefficient of performance (COP) of the heat pump, which allowed the same amount of heat to be produced with less electricity. Other electricity consumption (e.g., lighting, equipment) and domestic hot water demand remained unaffected by the studied heating system configurations.

Fig. 11 further illustrates the peak purchased power demand and the duration curves of backup heating power under the average weather scenario (TRY2020). As shown in Fig. 11(a), the LTDH cases with renovated low-temperature radiators (A-LTDH-60/30-LTR and B-LTDH-60/30-LTR) exhibited peak power distributions similar to the reference case. In contrast, LTDH cases with original radiators and backup heaters showed lower district heating peak power but significantly higher electricity peak power. The increase in electricity peak demand was 77%–169% for electric heater cases (A-LTDH-80/50-EH and B-LTDH-70/40-EH) and 38% for the heat pump case (A-LTDH-80/50-HP). Higher radiator temperature levels led to higher electricity peak loads. This finding contrasts with the minor share of backup heating in annual energy demand shown in Fig. 10, indicating that despite its limited contribution on a yearly basis, backup heating can be required intensively at certain times. This is confirmed by the backup heating

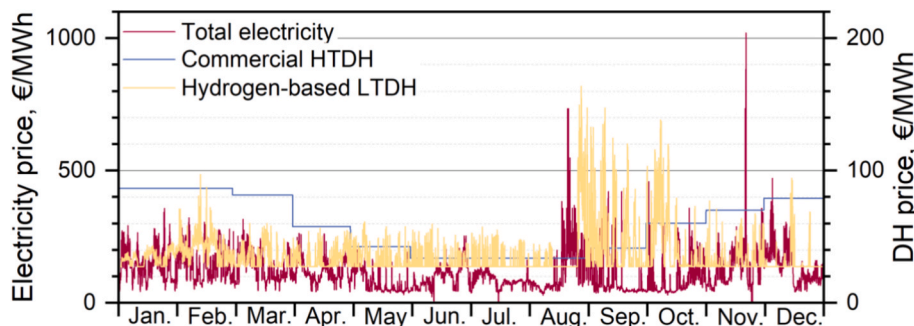


Fig. 9. Total electrical energy price (including energy price, electricity tax, marginal fee and transmission fee) and district heating prices with taxes included.

electricity power duration curves in Fig. 11(b), which shows that high backup power demand was concentrated in short periods, while for most of the year the backup power demand remained low. Moreover, similar to the purchased energy results, the use of a heat pump effectively reduced the electricity peak demand, due to its high COP.

3.1.2. Current and future weather scenario

Energy simulations were also conducted under different weather datasets (see section 2.2.1) to evaluate the performance of the studied cases across various scenarios. Table 9 compares the key energy performance of LTDH cases with backup heaters.

The results indicate that under current climatic conditions, interannual weather variability primarily affects the peak power demand of the DH and electricity, particularly the electricity peak load. In the cold weather year (Year 2016), the studied systems exhibited significantly higher electricity peak demand and lower LTDH peak demand. This is

attributed to the substantially lower outdoor air temperatures during the cold hours compared with other years, which led to higher radiator setpoint temperatures and, consequently, increased reliance on backup heating systems during cold hours. Conversely, in the warm year (Year 2023), LTDH peak demand increased while electricity peaks declined. In comparison, the effect of interannual variability on the annual purchased LTDH and electricity demand was relatively minor, remaining within 1% and 4%, respectively.

Similarly, under the warmer future climate scenario (TRY 2050, RCP4.5), the studied systems demonstrated higher LTDH peak power and total consumption, accompanied by lower electricity peak power and total electricity use. However, compared with the interannual fluctuations under current conditions, the impact of long-term climate change on peak power demand was less pronounced, while its influence on annual energy consumption became more significant. This suggests that current interannual variations are mainly characterized by short-

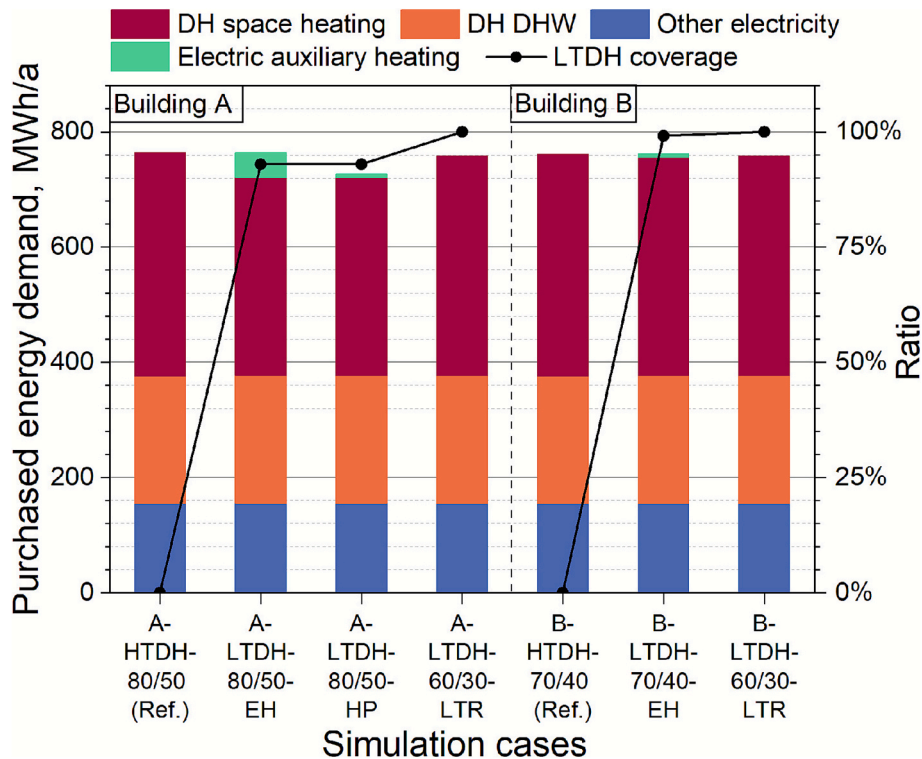


Fig. 10. Total annual purchased energy consumption and LTDH coverage of simulation cases for the average weather scenario (TRY2020), LTDH coverage represents the coverage of total heating demand covered by LTDH.

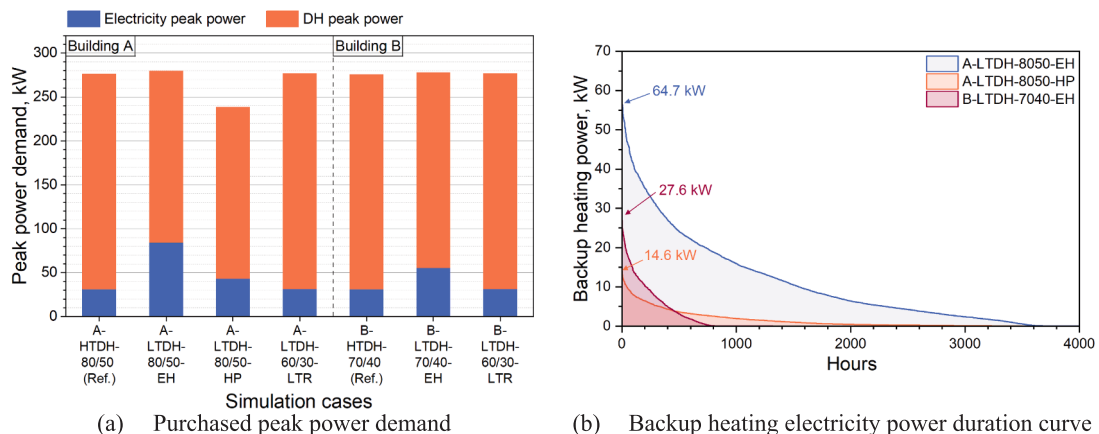


Fig. 11. Purchased peak power demand and backup heating power duration curves of simulation cases for the average weather scenario (TRY 2020).

Table 9
Energy performance of LTDH cases with backup heaters for different simulation scenarios.

Cases	Results	TRY2020 (Average)	Year 2016 (Cold)	Year 2023 (Warm)	TRY 2050, RCP 4.5 (Future)
A-HTDH-80/50-EH	LTDH coverage	93%	93%	94%	95%
	DH demand compared to reference case	93%	93%	94%	95%
	Electricity demand compared to reference case	128%	126%	124%	118%
	DH peak power compared to reference case	80%	75%	87%	83%
	Electricity peak power compared to reference case	269%	312%	207%	222%
A-HTDH-80/50-HP	LTDH coverage	93%	93%	94%	95%
	DH demand compared to reference case	93%	93%	94%	95%
	Electricity demand compared to reference case	104	104%	104%	103%
	DH peak power compared to reference case	80%	75%	87%	83%
	Electricity peak power compared to reference case	138%	145%	115%	116%
B-HTDH-70/40-EH	LTDH coverage	99.1%	98.9%	99.6%	99.5%
	DH demand compared to reference case	99.2%	99.0%	99.7%	99.7%
	Electricity demand compared to reference case	104%	104%	101%	102%
	DH peak power compared to reference case	91%	87%	97%	93%
	Electricity peak power compared to reference case	177%	193%	119%	135%

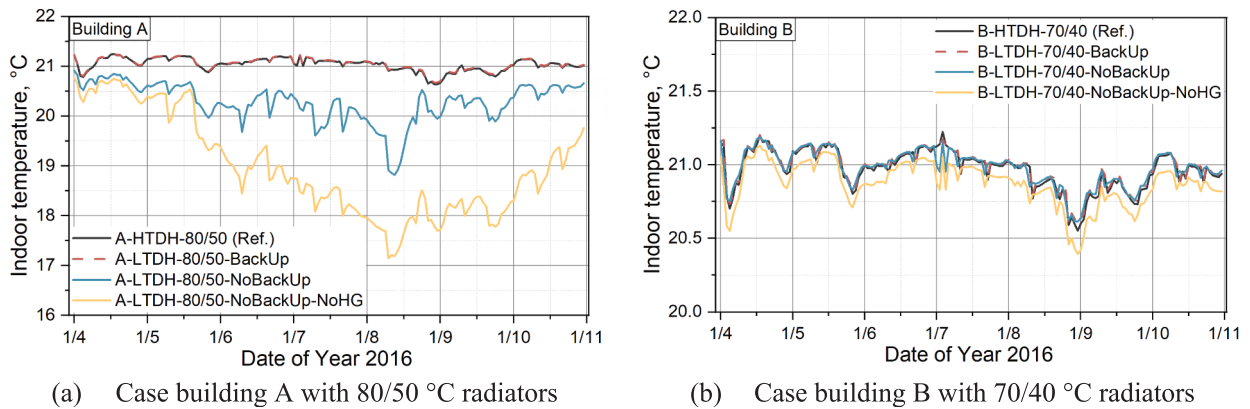


Fig. 12. Indoor air temperature of the coldest bedroom of the studied cases in 2016.

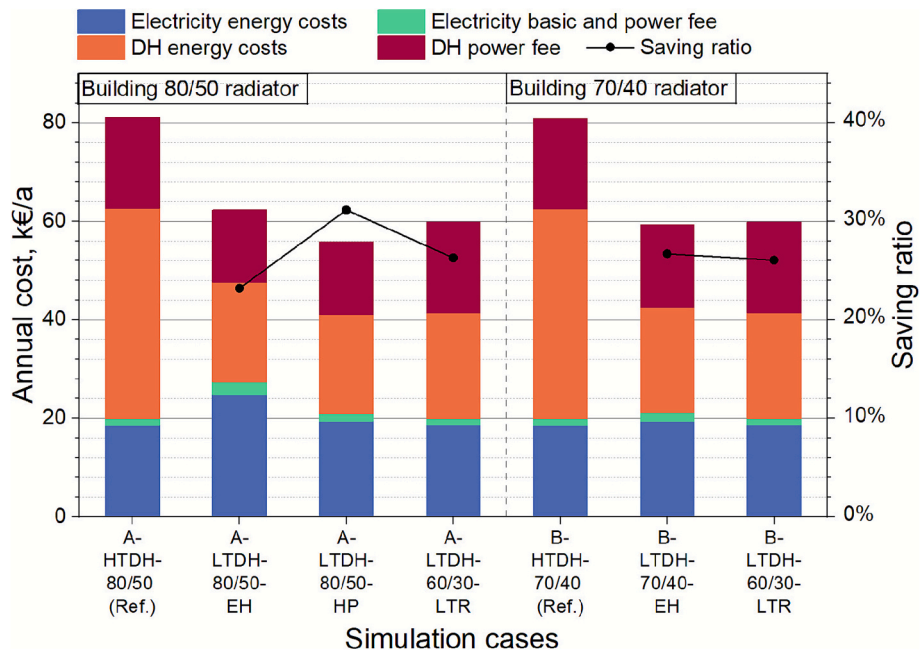


Fig. 13. Annual operational cost of simulation cases for the average weather scenario (TRY 2020).

term extreme events, whereas future climate change primarily alters average temperature patterns, leading to sustained shifts in overall energy demand.

3.2. Resiliency analysis

The results are shown in Figure 12. For the case building A with 80/50 °C radiators, the combination of LTDH and a backup heater (A-LTDH-80/50-BackUp) maintained indoor temperatures comparable to those of the conventional HTDH heating configuration (A-HTDH-80/50). In contrast, when no backup heating was applied (A-LTDH-80/50-NoBackUp), the minimum indoor temperature dropped below 19 °C. Excluding internal heat gains (A-LTDH-80/50-NoBackUp-NoHG) further reduced the minimum indoor temperature to 17.1 °C, which is below the minimum indoor temperature of 20 °C recommended for retrofitted apartment (category II) by the EN 16798-1: 2019[39] standard and may pose risks to occupant health and safety. These results indicate that despite the minor annual backup heating demand in old apartment buildings with high-temperature radiators, backup heating remains essential for ensuring indoor comfort during cold periods.

On the other hand, Figure 12(b) shows the indoor temperature of the coldest bedroom in the demonstration building B with 70/40 °C radiators during the same week. In this case, all scenarios exhibited similar temperature levels, and the impact of backup heating on indoor conditions was minimal, even during the coldest period. This suggests that LTDH could potentially be applied without backup heating in old apartment buildings equipped with 70/40 °C radiators.

3.3. Economic analysis

The economic analysis was conducted based on the simulated energy results under the average weather scenario (TRY2020) and the applied energy tariffs and investment costs. Fig. 13 shows the breakdown of the annual operational costs of the studied cases. The labels above columns refer to the total operational cost saving ratio compared to the reference cases. Compared with the reference cases, all LTDH cases demonstrated significantly lower energy costs, with savings ranging from 23.2% to 31.2%. This advantage primarily resulted from the substantially lower district heating costs, driven by both reduced annual district heating demand and peak power, and more importantly, the significant price benefit of hydrogen-production-based LTDH compared with commercial HTDH during the heating season (see Fig. 9). In this case, although cases with backup heating exhibited higher electricity costs than the reference cases, the overall energy costs were still considerably reduced.

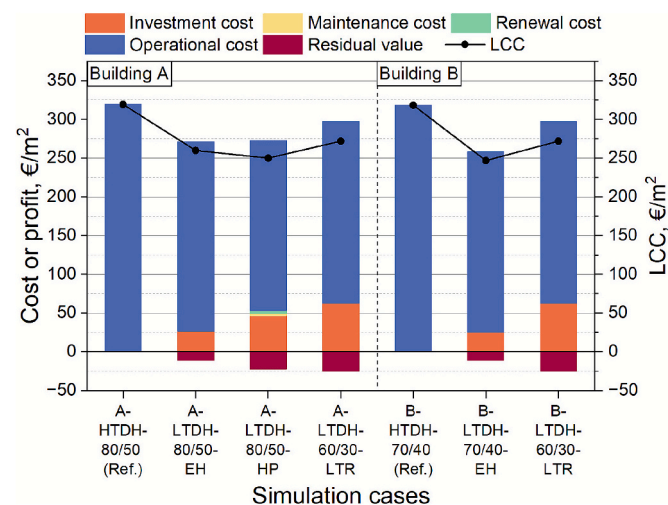


Fig. 14. Breakdown of life cycle cost of simulation cases for the average weather scenario (TRY 2020).

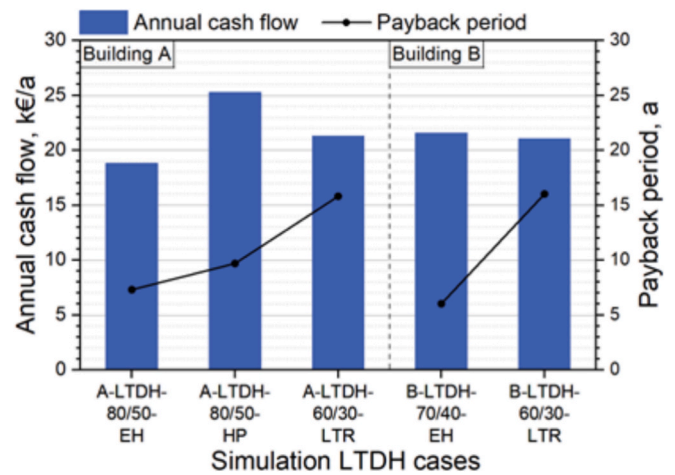


Fig. 15. Annual cash flow and payback period of simulation cases for the average scenario (TRY 2020).

For the case apartment with 80/50 °C radiators, the most cost-effective LTDH option was to retain the existing radiator system with a heat pump (A-LTDH-80/50-HP), which reduced district heating costs while keeping electricity costs relatively low. Renovating the system with low-temperature radiators (A-LTDH-80/50-LTR) was the secondary option. In contrast, the electric heater case resulted (A-LTDH-80/50-EH) in higher operational costs, mainly due to increased electricity consumption, including energy costs and power fees. For the case building B with 70/40 °C radiators, the two investigated LTDH solutions showed very similar operational costs. The electric heater option (B-LTDH-70/40-EH) showed a slight advantage, as the additional electricity cost was marginally lower than the savings in district heating costs.

Fig. 14 presents the LCC results of the studied cases under the average weather scenario. Despite the additional investment required, all LTDH solutions achieved lower LCCs compared with the reference cases, with the saving ratio of 15%–22%. This indicates that proposed LTDH solutions are economically feasible for old apartment buildings. This LCC saving was mainly driven by substantially lower operational energy costs. In addition, some subsystems retained residual value after the 25-year calculation period, which further contributed to the reduced LCC.

The results also highlight that retaining the original radiators with backup heating was more cost-effective than replacing them with low-temperature radiators. This finding was consistent across both studied case buildings and can be explained by the high initial investment of radiator renovation, which was not offset by corresponding reductions in operational costs. Furthermore, for the 80/50 °C radiator case, the heat pump solution (A-LTDH-80/50-HP) proved more LCC saving than the electric heater solution (A-LTDH-80/50-EH). Although the heat pump required a higher initial investment and incurred maintenance and renewal costs, its lower operational costs and residual value provided a net economic benefit.

Fig. 15 presents the annual cash flow and discounted payback period of the studied cases. Compared with the LCC results, the payback periods showed a stronger dependence on the initial investment costs. As a result, despite the lowest annual cash flow, the electric heater solutions (A-LTDH-80/50-EH and B-LTDH-70/40-EH) had the shortest payback periods, given their low initial investment. The payback period was 7.3 years for the 80/50 °C radiator case (A-LTDH-80/50-EH) and 6.0 years for the 70/40 °C radiator case (B-LTDH-70/40-EH), making the electric heater option more attractive from an investor's perspective.

The heat pump solution (A-LTDH-80/50-HP) achieved the second-shortest payback periods within 10 years. In contrast, the radiator renovation options (A-LTDH-60/30-LTR and B-LTDH-60/30-LTR)

showed significantly longer payback periods of around 16 years due to its high initial investment, despite the potential savings in operational costs. This makes the radiator renovation solution a comparatively higher-risk investment for old apartment buildings.

4. Discussion

This study demonstrates that hydrogen-production-based waste heat LTDH can technically meet the heating demand of old apartment buildings, with coverage levels largely dependent on the design temperature of the radiator systems. Buildings equipped with renovated low-temperature radiators (60/30 °C) were fully compatible with LTDH and required no backup heating. By contrast, in buildings with high-temperature radiators, backup heating remained essential to ensure indoor comfort. However, for these buildings, the annual contribution of backup heating remains limited, accounting for less than 10% of the total heating demand. This result contrasts with earlier studies, which reported significantly lower LTDH coverage for apartment buildings and a higher reliance on backup heating [37]. The difference can largely be attributed to differences in the assumed LTDH supply temperature. In this study, a constant supply temperature of 65 °C was adopted, which is relatively high and is sufficient to directly meet DHW demand without auxiliary heating and to satisfy space heating requirements for most of the year. In practice, however, LTDH supply temperatures may fluctuate and even fall below the level required for DHW production. Under such conditions, reliance on backup heating could increase significantly, highlighting the importance of accounting for variable supply temperatures in future evaluations.

The resiliency analysis further revealed that, in buildings with 80/50 °C radiators, LTDH without backup heating resulted in indoor temperatures falling far below the design setpoint, especially when internal heat gains were excluded. Backup heating is therefore essential for maintaining occupant comfort and safety during extreme cold events. In contrast, buildings with 70/40 °C radiators maintained acceptable indoor temperatures across all scenarios, indicating that LTDH could technically operate without backup heating. This finding is consistent with conclusions from several previous studies [7,8,40,41], which suggest that the oversizing of heating systems in existing buildings often provides sufficient margin for operation at lower supply temperatures. Nevertheless, the reduced capacity of radiators supplied with water below their design temperature increases the risk of temperature drops during extreme cold periods, such as the −34.3 °C event recorded in Helsinki in 1987. From a resiliency perspective, backup heating remains a robust choice, even if its annual use is limited.

The economic analysis showed that LTDH is cost-competitive compared with HTDH. However, the distribution of economic benefits varies with perspective. From a life-cycle perspective, heat pump solution offered the highest savings due to its high efficiency and residual value. From an investor's perspective, electric heaters were more attractive, given their low initial cost and short discounted payback periods, despite their higher operational costs and additional stress on the electrical grid. Radiator renovation improved long-term compatibility with LTDH but was disadvantaged by its high initial investment, resulting in lower LCC and longer payback periods. This disagreement reflects the tension between short-term investment appeal and long-term system optimization. Policy interventions, such as subsidies for radiator renovation or incentives for low-carbon heating technologies, may therefore be required to balance investor interests with long-term energy efficiency and decarbonization objectives.

Several practical challenges must also be acknowledged. Heat pumps, while efficient, require additional technical space, maintenance and noise mitigation measures, which are not always available in dense urban environments. Electric heaters are easier to integrate but impose substantial peak loads on existing electrical infrastructure, often exceeding the capacity of older apartment buildings and require costly grid upgrades. Renovating radiator systems ensures compatibility with

future LTDH supply levels but requires major construction works, which might cause temporary disruption of occupant comfort. Besides, its need for larger radiator surfaces may not be feasible in all existing apartments.

Another critical issue is the interaction with the power grid. Compared with the HTDH reference, LTDH systems with backup heating, particularly those using electric heaters, exhibited significantly higher peak electricity demand. This represents a transfer of peak loads from the DH network to the power grid, raising concerns over grid stability during cold periods when both heating and electricity demands are elevated. Possible mitigation strategies include integrating short-term thermal storage and enabling a demand response approach, which would allow short-term peaks to be smoothed over longer periods. While these measures can enhance system flexibility and reduce peak demand, their cost-effectiveness depends on additional investments in storage and control technologies.

The LTDH tariff in this study was based on leveled production costs with a 6% discount rate. Once profit margins and market conditions are considered, actual prices may be higher. Nevertheless, several factors suggest that LTDH will remain cheaper than HTDH. From the consumer's perspective, LTDH represents a lower-quality energy stream and should be priced accordingly. From the supplier's perspective, lowering supply temperatures improves overall system efficiency, reduces return temperatures, minimizes heat losses, and facilitates the integration of low-grade and renewable heat sources. Moreover, waste-heat-based production has inherently lower costs than conventional DH production methods. These factors suggest that LTDH has a structural cost advantage over HTDH, even when accounting for market uncertainties.

Several limitations must be noted. First, the analysis assumed that radiators in old apartment buildings remain in good condition throughout the life cycle, whereas in practice, many systems may require renovation or replacement, which could increase the relative attractiveness of radiator retrofit solutions. Second, the study focused on a single case building in Helsinki, constructed in 1969, which limits the generalizability of the results. Different years, layouts, and climate zones may lead to different outcomes. Third, the assumption of a constant LTDH supply temperature of 65 °C may not fully capture real operational dynamics, where fluctuations are expected. In addition, the residual values adopted in this study were derived from previously published research [27] conducted under similar building, climatic, and economic conditions. However, these values may be either overestimated or underestimated depending on actual implementation. This may introduce uncertainties in the economic assessment results.

Future research should therefore examine the performance of LTDH systems under variable supply temperatures, include sensitivity analyses of radiator conditions, and expand the scope to buildings of different years and climate zones across the Nordic region. Further attention should be given to the integration of distributed thermal storage, demand response, and advanced control strategies, particularly in the context of dynamic energy tariffs. These developments are expected to play a critical role in reducing consumer costs, enhancing flexibility, and ensuring the long-term viability of LTDH systems in old apartment buildings.

5. Conclusions

In this study, the feasibility of hydrogen-production-based waste heat low-temperature district heating (LTDH) usage in Nordic old apartment buildings is studied. Two case apartment buildings with conventional district heating (DH) and different high-temperature radiator systems (80/50 °C and 70/40 °C) were investigated as a reference. Based on the reference case buildings, two types of LTDH solutions were proposed to address the temperature mismatch between existing high-temperature radiators and LTDH: (i) retaining the existing high-temperature radiators while adding an electric heater or a heat-pump (HP) as a backup heater; or (ii) replacing the existing

radiators with low-temperature radiators (60/30 °C) directly connected to the LTDH network. The proposed solutions were modelled and simulated in IDA ICE 5.1 under multiple weather scenarios, complemented by a resilience assessment for extreme cold events. Moreover, their economic feasibility was evaluated by life cycle cost (LCC) and discounted payback period under the average weather scenario. The main findings are as follows:

- Under all studied weather scenarios, for the cases retaining existing radiators with a backup heater, LTDH can satisfy most of the building's total heating demand, with coverage of 93–95% for cases with 80/50 °C radiators and 98.9–99.6% for cases with 70/40 °C radiators. For the cases with low-temperature radiators, LTDH couples effectively with the radiator system and fully meets the heating demand.
- Under current climatic conditions, interannual weather fluctuations have a minor effect on the annual energy demand of LTDH systems with backup heating but show a significant influence on peak power behavior. For the case buildings with 80/50 °C and 70/40 °C radiators, utilizing the electric heater in cold year (Year 2016) increased electricity peak demand by up to 169% and 77%, respectively, while reducing LTDH peak demand. In contrast, the warm year (Year 2023) exhibited the opposite trend. The use of heat pump mitigates the grid stress compared with electric heaters, with the highest observed increase in electricity peak demand of 38%.
- Compared with interannual weather fluctuation, the long-term climate change (TRY2050) shows a smaller impact on peak power demand but a more pronounced influence on total energy consumption. However, backup peak demands remain remarkable: relative to the reference, peak electricity demand increases by 35–122% for electric heater solutions and by around 16% for the HP solution.
- The resiliency analysis results indicate that: for the building A with 80/50 °C radiators, a backup heater is essential to maintain indoor temperature during severe cold events, despite the limited annual backup heating demand. Without the backup heater, indoor temperatures can fall to 19 °C, and even to 17 °C when internal gains are excluded. By contrast, for the building B with 70/40 °C radiators, the lack of the backup heater has a minor temperature impact, indicating that LTDH can technically operate without backup heating.
- For the operational cost results: All LTDH solutions deliver substantial operational cost reductions of 23.2–31.2%. Savings arise primarily from the lower DH energy cost, driven by both reduced annual DH consumption and the significantly lower LTDH energy price during the heating season compared with commercial DH tariffs. For the building A with 80/50 °C radiators, the heat pump configuration achieved the lowest operational cost, followed by the low-temperature radiator configuration and the electric heater configuration; for the building B with 70/40 °C radiators, the solutions yield similar operational costs.
- Combining LCC and payback period results, all LTDH solutions are economically feasible, achieving 15–22% LCC savings relative to the HTDH reference. Among the LTDH options, the low-temperature radiator renovation solution shows the weakest economic competitiveness due to the highest LCC and the longest payback, reflecting substantially higher initial investment. For the building B with 70/40 °C radiators, the electric heater solution is the cost-optimal choice. For building A with 80/50 °C radiators, the HP-LTDH solution shows the lowest LCC, whereas the electric heater-LTDH solution achieves the shortest payback period.

The study result provides practical guidance for scaling the LTDH system in the existing apartment stock. Moreover, the findings support greater integration of renewable and recovered heat, and facilitate transitions from conventional DH to lower-temperature systems. In addition, the analysis provides guidance for implementing hydrogen-

production-based waste heat LTDH in older apartment buildings. The conclusions are transferable to regions with comparable climatic and economic contexts.

6. Declaration of generative ai and ai-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT 5.0 in order to improve the readability and language quality of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRedit authorship contribution statement

Jiayi Liu: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Yuchen Ju:** Software, Data curation. **Risto Kosonen:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Juha Jokisalo:** Writing – review & editing, Resources, Project administration, Data curation, Conceptualization. **Altti Meriläinen:** Writing – review & editing, Resources. **Antti Kosonen:** 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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Data availability

The authors do not have permission to share data.

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