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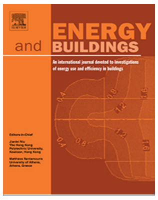

Renewable energy resources and multi-energy hybrid systems for urban buildings in Nordic climate

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ABSTRACT

This research conducts a technical and economic feasibility study of multi-energy hybrid systems (MEHS) combining different renewables for a northern climate city of Finland to address issues of replacing fossil energy by renewable energy sources (RES) to achieve zero carbon emissions. The renewable energy systems MEHS include geothermal, biomass and solar energy. The selected city-study site is the Olympic Training Center occupied by heterogeneous buildings which presents a good representative urban city for the assessment of the energy supply and demand. A generic and integrated modeling framework grounded in a combination of novel forecasting models for the heterogeneous building energy demands, the splitting of space heating and hot water use, the coupled renewable energy generation, and the time series electricity market is developed to investigate optimal MEHS configurations based on the technical and financial analysis. Innovative scenarios of MEHS are developed. The analysis results show that MEHS can flexibly meet the energy demand for the heterogeneous buildings and the optimal configurations can be realised by an innovative integration of geothermal and solar sources as well as electricity as complementary energy. Model uncertainty and its impacts on the analysis are also considered and discussed.

1. Introduction

Although renewable energy, particularly solar and photovoltaic (PV) energy, has increased dramatically and the cost of solar panels has fallen almost 90 % in the last 10 years, global energy consumption still keeps growing around 1–2 % per year due to the increases in populations and people's wealth [1]. The growth of energy consumption challenges low-carbon transitions in building sector. In 2020 for example, buildings accounted for 36 % of global final energy consumption and nearly 40 % of energy related carbon dioxide (CO2) emissions. In the EU, over 75 % energy used in heating, ventilation and air-conditioning (HVAC) systems was from fossil fuel in buildings [2]. Large-scale deployment of hybrid renewable energy sources (RES) is considered as a key for building sector to achieve zero carbon emissions. And for that, RES must content with building energy demand.

Due to the intermittency of RES, multi-energy hybrid systems (MEHS) combining different renewables have been considered a viable solution that allows RES to improve their reliability levels for a wide spread of renewables. However, balancing building energy demand and RES supply faces a range of technological, economic, social and political challenges at different building scales: from single buildings to communities, districts and urbans, because neighbourhood effect and local availability of RES are important factors for the successful deployment of RES and the local spatial-temporal features manifest different RES, energy systems and their interactions.

In the literature, different perspectives on buildings and related spatial scales, e.g. single, neighbouring, community, district, and urban buildings, have been investigated regarding this issue over a range of RES. The most popular RES are solar PV (e.g. applied to energy communities in Austria [3] and to New York city [4]), wind energy (e.g. deployed to Ajloun of Jordan [5]), tidal energy (e.g. used in three ports in Iran [6]), geothermal energy [7–9], biomass energy (e.g. applied to an Italian district [10] and rural communities [11]), hydro energy, waste energy [12] and MEHS [13]. The renewable energy infrastructures vary from single

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buildings [8], neighbourhood [12], communities [3], district [10] and urban cities [4,5]. Fathollahzadeh et al. (2021) presented an MEHS (wind and PV farms) analysis of technical and environmental feasibility for rural communities [14]. The results demonstrated better performance of MEHS than standalone renewables.

From methodological perspective, very different methodologies have been proposed that specifically target feasibility analysis of MEHS. de Doile et al. (2022) applied stochastic analyses on economic feasibility of MEHS (PV and wind with battery banks) for Brazil based on available databases [15]. Fina et al. (2020) developed an optimization model for large-scale application of rooftop PV systems for neighbourhood energy communities in Austria [3]. Economic sensitivity analysis was performed through the objective of maximizing the net present value (NPV) over 20 years. The results showed that the neighbourhood level of building community was not sufficient to optimise rooftop PV capacity. Giorgio and de M (2016) investigated economic feasibility of biomass-based plants that used local biomass wood in an Italian district where the population showed a declining trend [10]. The study was formulated as mixed integer optimization problem that was solved by a commercial software. Results showed that the optimal plan varied with the forecasted evolution of the energy demands. The local RES solution should not be extrapolated to different contexts. Ramos-Escudero et al. (2021) made a feasibility study of shallow geothermal for two residential customer areas in Spain [9]. Specifically, ground source heat pump systems and economic and environmental influences were investigated using the geothermal mapping model developed by Casasso and Sethi (2016) [16]. The model is based on analytical heat transfer approach to estimating the maximum thermal quantity obtained by a borehole heat exchanger during a heating or cooling season. Results confirmed the applicability of the shallow geothermal resources as heating and cooling supply. Wang et al. (2020) performed Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis and the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) method to study RES influential factors for two provinces in Pakistan [17]. Economic and socio-political were identified as the most important factors. He et al. (2021) proposed decision-making process based on filter's smoother evaluation of RES and validated in a province in China [18]. The results showed that a PV-wind-geothermal MEHS performed the best. Usman et al. (2022) studied MEHS in four climates by the multi-criteria decision making method using CRITIC-TOPSIS framework [19]. TRNSYS was adopted to simulate building energy load.

A variety of commercial software has also been employed. Ahmad and Zhang (2021) applied commercial software Hybrid Optimization Model for Electrical Renewables (HOMER) to investigate techno-economic feasibility of MEHS (PV, wind turbines, battery banks, power grids, and diesel generators) for grid-connected community [20]. HOMER was also used by Islam (2018) to investigate techno-economic results of three scenarios of MEHS (grid, hydro turbine and PV) for a grid-connected office building [13]. Nematian and Rahimi (2022) examined suitable locations of MEHS for cities in Iran using HOMER software for economic cost assessment [21]. Park and Kwon (2016) performed feasibility study on independent MEHS, including wind turbines, PV panels, converters, and batteries, for an island in South Korea using the HOMER software based on different economic criteria [22]. Schicker et al. (2022) performed a feasibility study of biomass-driven combined heat and power systems for rural communities based on the proposed models and EnergyPlus software [11]. Mahdieh et al. (2022) conducted feasibility analysis of wave and PV-sourced MEHS for three ports in Iran using MATLAB/Simulink [6].

These growing interests in MEHS reviewed in the literature demonstrate the diversity of feasibility study methodologies because different RES supply and energy demand interact in a complex manner. The comparison of sewage heat recovery and solar borehole thermal energy storage system for instance shows that the financial viability must be defined as site-specific depending on the local fossil fuel and electricity prices [12]. In a separate study of MEHS for four climates, different locations (Stockholm, Saarbrücken, Quetta, and Jakarta) created very different MEHS options [19]. Configuring, dimensioning, and operating MEHS optimally requires advanced modeling techniques to properly fit the particular needs for local requirements, such as the regional available RES [10,23]. Ahmed et al. (2022) presents the state of the art of recent advances in RES assessment towards net-zero energy buildings and identifies that the current research lacks a universal decision tool [24].

There is a need for a generic method of integrated planning and optimal operation of building energy demand, RES and supply-demand balance to effectively support the decision-making process of MEHS (see a comprehensive review by Horschig and Thrän (2017) [25] and a recent review by Bozgeyik et al. (2022) [26]).

This paper fills this gap by providing a generic and up-to-date feasibility assessment study as a methodological framework for decarbonising buildings across cities and regions. The major contribution of this paper includes long-range demand-supply strategies of MEHS planning for buildings with a set of novel forecasting models. According to UN data [27], the world's urban cities occupy only 3 % land yet consume 60–80 % energy and emit 75 % carbon emissions. To fully characterise urban buildings, the Olympic Training Center in Kuortane of Finland was particularly selected as a city-study site because it covers very different complex buildings, including sports facilities, residential and office buildings, to reflect different building features. This will ensure our generic framework is more robust to various instance scales and diversities. To capture the diversity of building energy demand profiles, a new building energy forecast model is proposed to split space heating and hot water consumptions. Geothermal energy of RES supply is focused because its feasibilities remain controversy in the scientific literature [28]. The utilization rate of shallow geothermal energy, for example, is low compared with other RES [29]. Kim et al. (2014) presented a feasibility study of lifecycle cost analysis for geothermal energy applied to a single building at its design phase [8]. The results showed that geothermal energy was not an economically feasible solution. Saaly et al. (2019) proposed a geothermal energy pile system with waste heat recovery applied to an institutional building in Canada [7]. The heat loss from geothermal piles was recycled to building's HVAC system. It was found that geothermal piles could not meet the building demand, hence auxiliary heat sources were suggested. Wiryadinata et al. (2016) investigated technical and economic feasibility of horizontal ground-loop geothermal energy for space conditioning in California of the USA. The decision process reveals that the viability of this technology is highly dependent on climates and building types [30]. Xu et al. (2020) summarized the shallow geothermal energy (200 m deep) for five geological regions in China [29]. The conclusion is that general measures of a feasible assessment and operational plan are needed to enhance the use of geothermal energy.

The very different building characteristics that signify diversity in building types in the Olympic Training Center allow to address these problems with geothermal energy (e.g. dependence on building types, low utilization rate, lack of measures of feasible assessment, etc). In particular, since the feasibility decisions depend considerably on the economic analysis, a plurality of feasibility study of MEHS is necessitated due to the diverse MEHS and adopted variety of analysis methods [18]. Assessing the marginal costs of MEHS deployment is an important issue worthy of study. In summary, this paper aims at addressing these research gaps by the following contributions:

- A Nordic climate Olympic Training Center is selected as a good representative and mini city with various types of urban buildings.
- Building energy demand forecast is proposed to split the total -heat use into the space heating and the hot water consumptions.
- A time-series autoregressive–integrated-moving-average (ARIMA) model is developed to forecast electricity prices.
- Innovative MEHS scenarios are developed using the proposed framework. The MEHS scenarios tested in paper are novel in the sense that some discussion points have not been presented in the literature.
- Economic and financial prices and payback periods of different MEHS configurations are compared and marginal costs are estimated, which provide a critical assessment of geothermal energy investments for urban buildings under Nordic climate. The literature lacks the studies of the economics of geothermal energy data and the few available data vary enormously [28].

2. Background of the city-study site

The Olympic Training Center in Kuortane of Finland was chosen to particularly reflect the characteristics of the Scandinavia urban cities. The training center is located in the western Finland (Fig. 1) with 223731 m^2 land area and is famous for its sports training, for instance Formula One training. The training center consists of diverse types of buildings with occupied building area 45500 m^2, including different sports facilities whose high energy intensities are well acknowledged. These buildings were heated by peat-fired boilers due to a prior agreement which will expire by 2023. The Kuortane Sports Institute as a private foundation supports the financing and deployment of clean energy of the city Kuortane and has planned to replace the existing peat with RES during our study period.

With regard to the RES, geothermal energy, solar energy and biomass from wood residues were the main options. This paper conducts a technical and economic feasibility study of MEHS, including geothermal, biomass and solar energy, to address issues of fossil fuel and carbon emissions and to help the municipality authorities and private foundations in making an investment decision. Specifically, viable prices of electricity and investment in geothermal energy are explored based on the projected electricity prices and unpublished project data. A generic and integrated techno-economic feasibility modeling approach is developed to carry out a comprehensive analysis of RES solutions and related costs for an optimal MEHS configuration based on the forecasted energy demands from different types of buildings, renewable energy supply and ARIMA time series analysis of the electricity prices. The proposed generic approach provides a practical tool for decision makers in various regional RES planning and investment projects.

Fig. 1. The chosen city-study site: The Olympic Training Center in Kuortane, fully representing the Nordic urban cities with heterogeneous types of buildings.

3. Generic modeling framework

The schematic diagram Fig. 2 illustrates the proposed generic modeling framework. The feasibility study is carried out using the combination of measured data and mathematical models. In cases where measurement data are not available, system modeling is employed. The main sections consist of demand model, supply model and electricity market. In section 3 (Generic modeling framework), demand-supply model and electricity market are presented based on measurement data and models. In section 4 (Results), the supply model, with a focus on geothermal energy, is presented with two-level analysis in order to develop innovative MEHS solutions.

3.1. Measurement data

3.1.1. Basic information and weather

Fig. 3 shows basic building information of the study site. Building construction grew 50 % over the last ten years.

The weather and solar irradiation data (Fig. 4) was extracted from the nearest weather station [31,32]. During our study period, solar PV systems were expected to be available in the following year with the estimated annual solar energy 669.4 MWh and solar panels 876.69 kWp.

3.1.2. Building energy demand

As the objective of feasibility study is to search different options of supplying the load demand for the optimum configuration of MEHS, a complete availability of the measured demand data, especially for heating, is necessary [33]. Fig. 5 presents the average heating consumption trend during 2010–2019. The declining trend is obvious given the 50 % growth rate for buildings. The average annual energy consumption per m^2 for all types of buildings was measured as 117 kWh/m^2 in 2019 which is much lower than the average value at EU level of about 180 kWh/m^2 [34]. Such a significant decrease is due to the local Kuortane Sports Institute's active endeavour to increase the building energy efficiency.

3.1.3. Electricity market

Electricity prices depend on many factors, such as local taxes, subsidies, carbon taxes and the sources of the power which vary enormously by locality within a country. Fig. 6 shows the fuel price variation in Finland [34].

3.1.4. The energy supply

The capacities of sizing the renewable supply are based on the energy measurement data for the latest available year 2019 as a reference year (Table 1).

Renewable energy supply (e.g. Table 2 for geothermal energy) covers the possibility of producing power and heat from available RES on the study region. In this study, mixed RES of geothermal and biomass energy are considered with solar PV energy because the PV system was being implementing and would be further

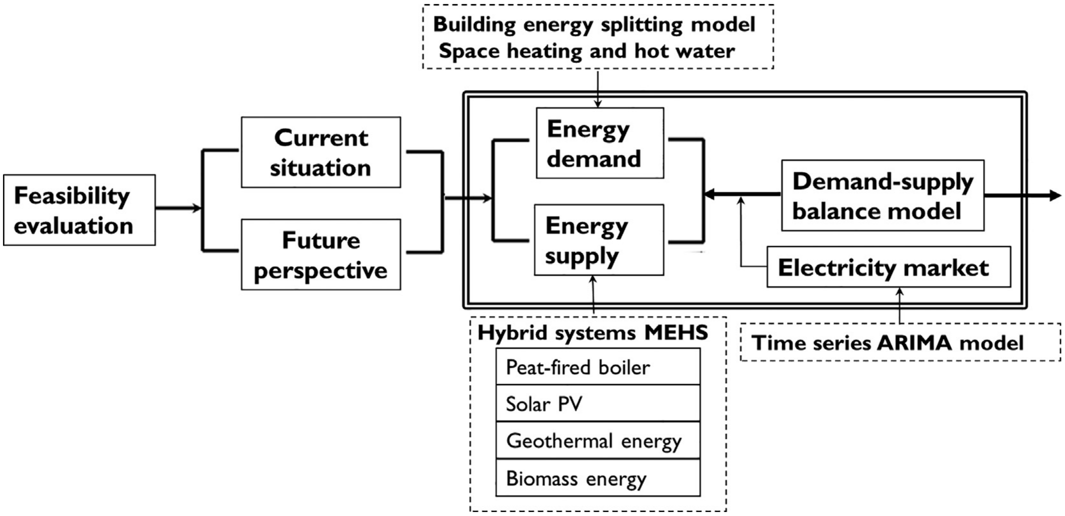


Fig. 2. The proposed generic modeling framework. The main sections (Generic modeling framework and Results) consist of subsections of demand model, supply model and electricity market.

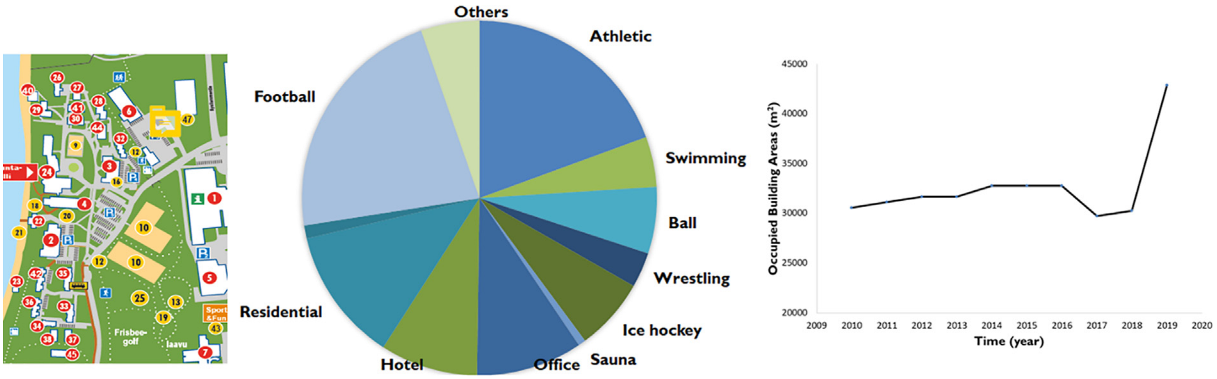


Fig. 3. Basic building information of the study site: The Olympic Training Center.

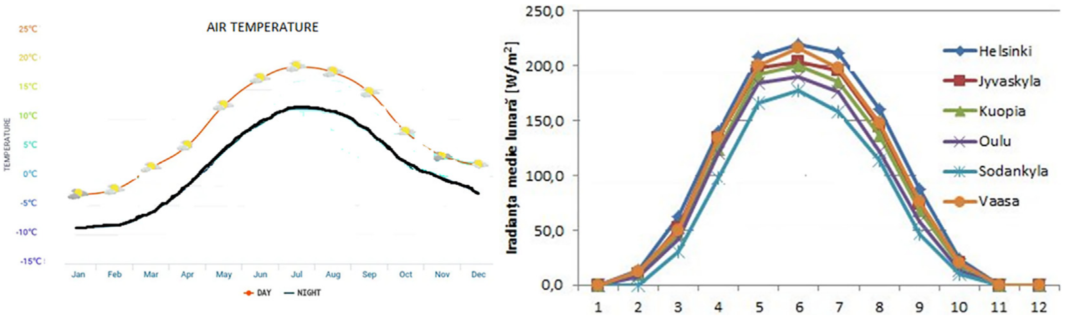


Fig. 4. The weather and solar data extracted from the nearest station [31,32].

enhancing at the stage of this study. Geothermal energy is an abundant heat source given the available 223 731 m^2 in the area. Unlike most intermittent renewables such as solar and wind, geothermal energy is steady and has been expanding quickly in the EU in recent years. However, according to the International Renewable Energy Agency (IRENA), the installed capacity worldwide has only increased from 10 GW to 14 GW during 2010–2019. The key challenges for geothermal energy use include high upfront costs of drilling and installation, land use and risk issues. A feasibility study is normally preceded the geothermal projects. However, geothermal wells are unique in each geothermal energy projects: even in the same field, they are more different than oil and gas wells, so the learning curve from experience is not very useful [35]. Consequently, the financial cost varies from one geothermal project to another, data of cost estimates are typically not available. Table 2 shows some of Finnish geothermal project data gathered from open source.

Based on the burial depth, two types of geothermal energy are considered: decentralized shallow geothermal energy (0–350 m) and centralized deep geothermal energy (1000–6000 m). Since the geothermal heat flow in Finland is very low with gradient of about 1–1.5 °C per 100 m, both types of geothermal energy require

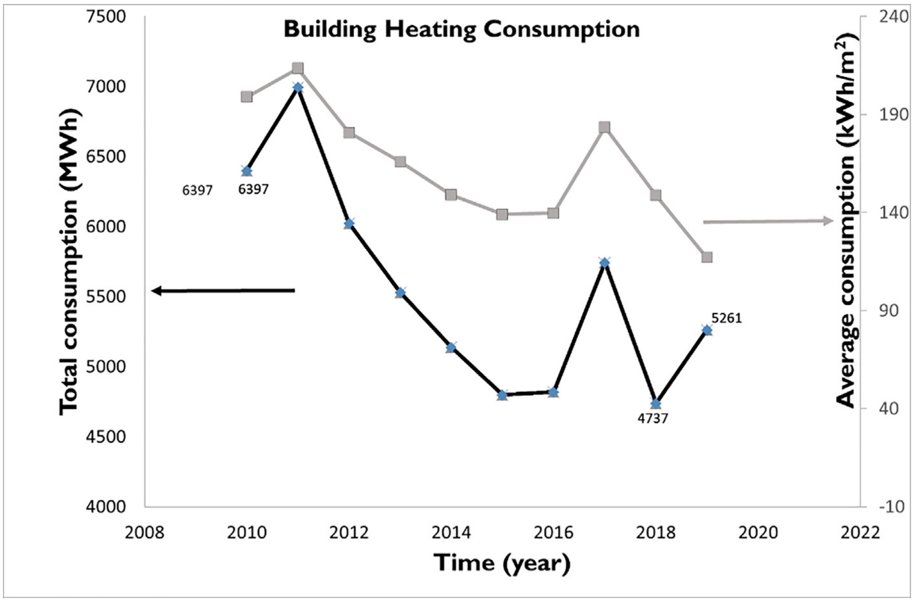


Fig. 5. Building heating consumption during 2010–2019.

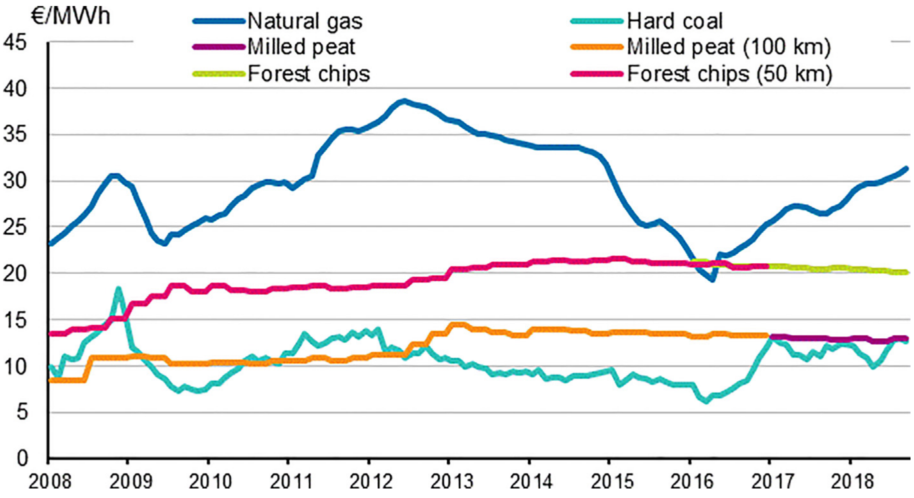


Fig. 6. Fuel price variation by sources in Finland [34].

Table 1
Measurements for the reference year 2019.

Building floor area 45 500 m^2 (year 2019)
Heating consumption 5261 MWh (5037 MWh excluding loss) (year 2019)
Heating peak 736 MWh in January (year 2019)
Seasonal heating consumption in winter 5076.8 MWh (year 2019)
Electricity consumption 2721 MWh (year 2019)
Domestic household electricity consumption 2444 MWh (year 2019)
PV production of annual 669.4 MWh and peak 876.69 kWp*

* Expected in the following year. Domestic electricity consumption for ice rink was excluded.

heat pumps to upgrade the temperature to a point that can be adequately fed into the space heating. A spatial analysis for both types of geothermal resources is conducted to estimate the required geothermal capacity. Then the land area needed to meet the corresponding geothermal capacity is calculated and the number of geothermal wells is derived. Our estimate shows that there is sufficient land for harvesting geothermal heat. The space availability to install heat pumps in building surroundings requires further investigation on site. For simplicity, feasibility study is conducted by assuming that the required land is available for both shallow and deep depth geothermal resources. Finally, price data of peat and biomass woodchips were provided by the Kuortane Sports Institute based on the contracts (shown in Results section).

Table 2
Geothermal project data from Finland.

Distance to the study region	Depth (km)	Liquid/fluid	COPs of Heat pumps	Instantaneous power (kW)	Continuous power (monthly, kW)	Annual production (MWh)
unavailable	0,3	28 % ethanol	3–4	8–25	5–7	24–30
335 km south	1.3	water	3.5–4.5	500	250–300	> 1 000
115 km southern east	1.5	water	3.3–4.5	480	–	1500
345 km south	6.4	water	9	10000–30000	10000–30000	80000–240000
175 km south	6–7	water	9	6 000	3000	18,000

3.2. Models

An integrated modeling framework grounded in a combination of a set of novel forecasting models for the heterogeneous building energy demand patterns and the coupled RES with time series prediction of the electricity prices is needed to investigate an optimal MEHS based on the technical and financial analysis. In the following, we propose a generic modeling framework for an integrated set of the needed models and analysis.

3.2.1. Building energy demand for space heating and hot water

Because buildings often have single meters for both space heating and hot water, splitting of the energy use for them is needed. However, choosing how to model the split of the data is not a trivial task. The recent paper by Ivanko et al. (2021) made an assumption that the outdoor temperature is the main parameter influencing the space heating whilst the hot water use is independent of outdoor temperature [36]. An energy signature curve was then introduced describing the relationship between the dependence of space heating and outdoor temperature. Using regression analysis and singular spectrum analysis, the modeled space heating was extracted from the measurements. In previous literature, different types of models have also been proposed, such as non-parametric kernel smoother regression model [37], neural networks [38] and seasonal characteristics-based model [39]. These models targeted residential buildings. This study presents more complex challenges in that different types of buildings were involved with different heating and hot water use profiles [40].

A new multiple linear regression model is proposed to address these complex issues. The model assumes that there is a linear relationship between the total load and the usage for space heating and hot water for each type of buildings:

$$y_i = \alpha_{i0} + \alpha_{i1}X_{i1} + \alpha_{i2}X_{i2} + \varepsilon_i \tag{1}$$

where

y = total load.
i = building type, for example, residential, office, sports, etc.
X_1 = space heating consumption.
X_2 = hot water consumption.
α = regression coefficient.
ε = model error.

The parameter i captures heterogeneity across different building types and load profiles modeled by the method we proposed previously [41]. The best-fit model is obtained from the regression coefficients α that should lead to the smallest overall model error ε. Both the two-sided t-statistic of the model and the p-value are estimated. The t-statistic determines if the linear relationship is true and the associated p-value determines the probability of the t-statistic assuming the Null Hypothesis of no relationship between the independent and dependent variables is correct. A p-value ≤ 0.05 means statistically significant, indicating strong evidence against the Null Hypothesis [42].

3.2.2. Electricity market

Electricity price forecasting has attracted extensive interests since the introduction of the deregulated electricity markets. Electricity generation companies sell electricity and energy suppliers buy it and sell to customers in the market. Transmission system operators are responsible for the transmission grid and the wholesale markets are managed by independent system operators or regional transmission organizations. All of these market producers and operators require accurate electricity price forecasts in order to maximize their profitability. Electricity price forecasting has received considerable attention in recent years, however, accurate forecasting approach still lacks in the literature [43] due to the complex which involves multiple participants and influential factors. Forecasts generally include short-term and long-term predictions which rely on different forecasting approaches. Short-term forecasting typically involves hourly or daily predictions of the electricity prices whilst long-term forecasting targets at yearly predictions. Economic feasibility analysis of renewable energy requires long-term electricity prices on the investment time horizon which is at least ten years. A long-term electricity price forecasting significantly increases the uncertainty chances due to the long-time horizon that involves many modeling challenges [44]. We propose the following ARIMA time series model

$$pe_t = \beta_0 + \beta_1 pe_{t-1} + \beta_2 CO2_t + \beta_3 pf_t + \varepsilon_t \tag{2}$$

where

t = time (year).
pe = electricity price.
$CO2$ = carbon tax.
pf = fuel price.
β = regression coefficient.
ε = model error.

Eq. (2) presents a parsimonious form, for example pf presents fuel price that includes oil, coal and gas (see Fig. 6). The model error ε presents an uncertain random process that causes model errors. Eq. (2) is a first-order autoregressive (AR(1)) model if the error term ε is an identically distributed (i.i.d.) zero-mean Gaussian process. The best fit model parameters β are determined according to the Akaike information criterion (AIC) [45]. Normalization is recommended for the means and standard deviations to remove errors prior to data analysis. Details of model identification procedure can be found in the classical book by Box and Jenkins (1970) [46].

4. Results

4.1. Building energy demand

Here we choose 5400 MWh and 736 MWh as the annual and peak demand capacity for sizing the MEHS. The chosen 5400 MWh is about 4 % higher than both the 2019 consumption 5196 MWh and the average value of the recent six years (see measurements in Table 1 and Fig. 5). The peak consumption 736 MWh in January is the highest among the recent six years based on the measurements. These selected values can be justified also by the following facts:

- The energy consumption trend is declining due to the increase of building energy efficiency, as described previously.
- Based on the heat meter reads, an average of 3 % heat is lost from the transmission lines.
- The average consumption value of the recent six years is about 5000 MWh. We size the system for 5 % higher of the average value (5400 MWh).
- The peak consumption for winter heating demand is 5076.822 MWh which is satisfied by 5400 MWh (see measurements in Table 1).

Using the local average outdoor temperature (Fig. 4), we simulate average annual energy demand and split it into space and hot water usage. The total annual heating demand is summed up as 5400 MWh (i.e. the heating demand capacity). The validation of the building energy demand model is displayed in Fig. 8 where household electricity breakdowns were averaged from the measurements.

4.2. Electricity market

Regarding the complex behavior of the electricity market prices, we consider two projection scenarios in the model (Eq. (2)):

Expected scenario: Based on the historical electricity market data (e.g. Electricity cost was 29.6 €/MWh (0 % VAT) in year 2019 and 47 €/MWh (0 % VAT) in 2020 + electricity transmission price + electricity tax) and the proposed ARIMA time series model (Eq. (2)), an auto-regressive conditional fitting is applied to project the data for year 2020–2031.

Worst scenario: In the worst scenario, it is assumed that the electricity price doubles and transmission price increases by 20 % for year 2020–2031.

These two scenarios are shown in Fig. 9 for comparison.

4.3. The energy supply

The plan for peat's RES upgrade is:

- Solar PV: from the measurement data.
- Geothermal: centralized (deep) and decentralized (shallow) systems for the lifespan of 30 years. The needed area for geothermal wells is available and the potential for the geothermal usage exists.
- Biomass: wood residues. The price is available for 2019 only and the contract will expire by 2026.

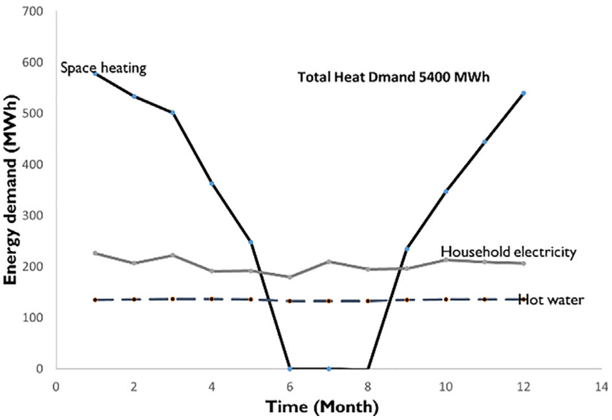


Fig. 8. Average energy use breakdown for all the buildings.

4.3.1. Solar PV

Based on the measurement data of the global horizontal solar irradiation and outdoor temperature (Fig. 4), the solar PV capacity 669.4 MWh/year in Table 1 and PV manufacturer specification 876.69 kWp, we modelled and calculated solar PV production potentials. Fig. 10 shows the results including monthly breakdown relative to the demand.

4.3.2. Geothermal energy

As geothermal energy systems are a capital-intensive technology, a two-stage analysis model is employed. A preliminary analysis is performed at the first stage. We use the in-depth analysis from preliminary results to explore potential optimal scenarios in the second stage.

4.3.2.1. Preliminary analysis. The potential of renewable geothermal energy of the area was calculated by the software tool ePotential (Fig. 11). ePotential consists of local soil properties that has been validated by experiments.

Based on the data of the available area for the Olympic Training Center, and the total floor area of buildings, the number of boreholes with desired depth can be estimated to satisfy the total demand and the peak loads: 1) the annual heat demand 5400 MWh; 2) the peak load demand in January 736 MWh; and 3) the seasonal winter load demand 5076.822 MWh (see Section 4.1). Utilizing the software ePotential, it is predicted the following scenario-based geothermal systems can fulfill the targets of the annual, seasonal, and peak demands:

Decentralized geothermal system: 187 boreholes 300 m deep. The total cost is about 2.2 M€.

Centralized geothermal system 1: 5 boreholes 1500 m deep. The total cost is about 4.8 M€.

Centralized geothermal system 2: 3 boreholes 2000 m deep. The total cost is about 4.5 M€.

The costs include the purchase of heat pump and installation costs also.

4.3.2.2. In-depth analysis. From the preliminary analysis, we can find that the geothermal energy systems tend to have high capital costs in terms of the peak load. Take the 1.5 km depth borehole as an example, 4×1.5 km boreholes are not enough for the required peak energy demand in January, but 5×1.5 km boreholes are over-sized which increases drilling cost. For the 2.0 km depth borehole, 2×1.5 km boreholes can satisfy the annual heating demand whilst are not enough supply for the required peak energy demand in January, 3×2.0 km boreholes are therefore needed. An innovative way to reduce the investment cost is to incorporate a small amount of grid electricity purchase into the geothermal energy supply system. In this scenario, instead of drilling 3×2.0 km boreholes which are over-sized and costly, 2×2.0 km boreholes are selected, because only small amount of peak heat in January can not be covered by 2×2.0 km boreholes. This way, the cost reduction can be achieved. Fig. 12 illustrates the innovative idea.

In this regard, the following MEHS scenarios are proposed:

Decentralized geothermal system: 187 boreholes 300 m deep. The cost is about 2.2 M€.

Centralized geothermal system: 3 boreholes 2000 m deep. The cost is about 4.5 M€.

Mixed centralized geothermal and grid system: 2 boreholes 2000 m deep. The cost is about 3.2 M€ + Electricity purchasing cost.

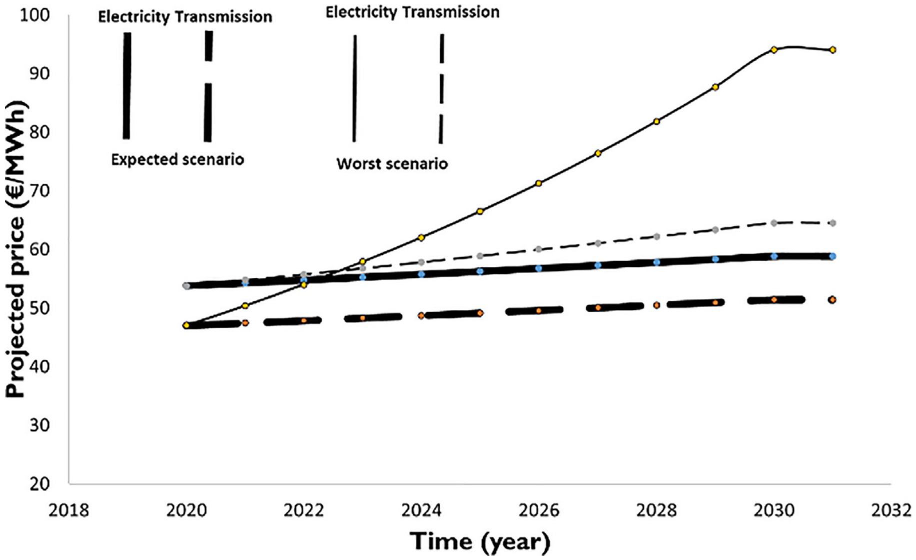


Fig. 9. Forecasts for electricity and transmission costs based on extreme and expected electricity price scenarios.

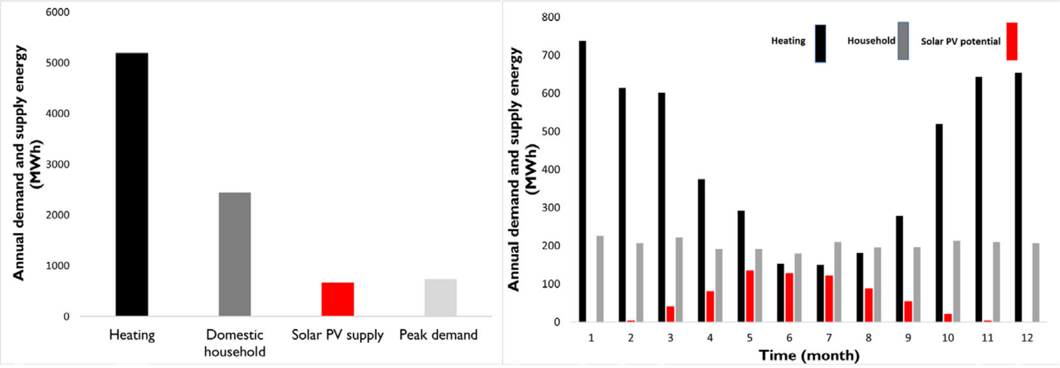
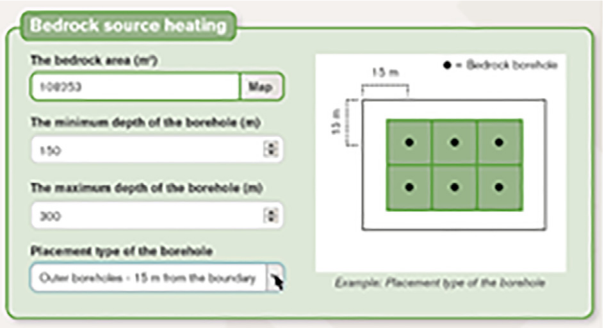


Fig. 10. Simulated supply–demand balance for solar PV potentials.


Bedrock source heating

The bedrock area (m²): 108253

The minimum depth of the borehole (m): 150

The maximum depth of the borehole (m): 300

Placement type of the borehole: Outer boreholes - 15 m from the boundary

Fig. 11. Illustration of the geothermal energy calculation tool ePotential.

4.4. Economic feasibility analysis

We conduct economic feasibility studies here for the innovative scenarios of MEHS, including solar, geothermal and biomass technologies. The year 2019 was chosen as the reference year to characterize the heating and electricity costs and credible quantitative estimates of the projected energy costs for the proposed three scenarios.

The actual heat energy cost was 291,535 € (5196 MWh) and the electricity cost was 189,969 € (2444 MWh) with 0 % Value Added Tax (VAT), leading to the total cost of 481,504 € for the reference year 2019. The demand-based energy cost is 299,448 € based on the heating demand 5400 MWh and the electricity cost is assumed to remain the same 189,969 €. The total cost will be 489,417 € with 0 % VAT. Fig. 13 illustrates the prediction results based on the expected and the worst scenarios of electricity prices including baseline technology of peat resource as well as biomass woodchips with 0 % VAT. For baseline and biomass technologies, only contract-based data are available. Fig. 14 presents the corresponding results where COPs of heat pumps are assumed as 3.1 and 4.2 for decentralized and centralized geothermal technologies, respectively. The payback time for geothermal resources is over ten years.

Further evaluation is performed for the reduction of the initial investment of deep geothermal resources by about 30 % supported by public funding, which presents the real cases in Finland. The government of Finland encourages sustainability and supports building renovation projects that benefit the environment, for example, by increasing the use of RES. Public funding for deep geothermal energy projects is available to leverage very high investment. Based on the renewables support policy, the mixed centralized geothermal and grid technology (2 boreholes plus purchased electricity) becomes the feasible option with the expected electricity prices as shown in Fig. 15.

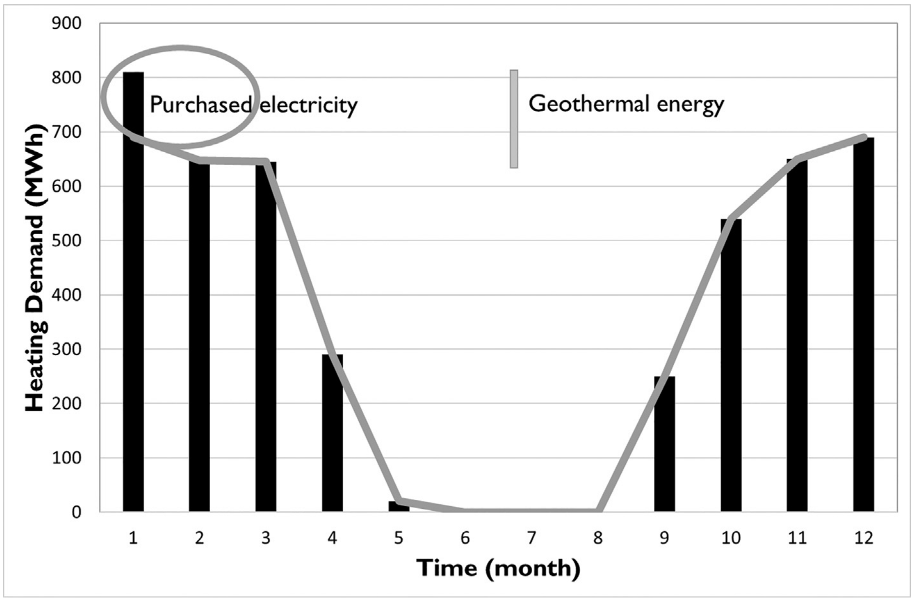


Fig. 12. An innovative idea: geothermal source combined with electricity purchasing.

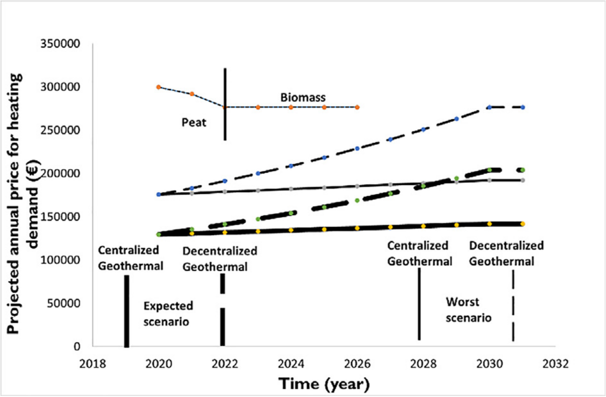
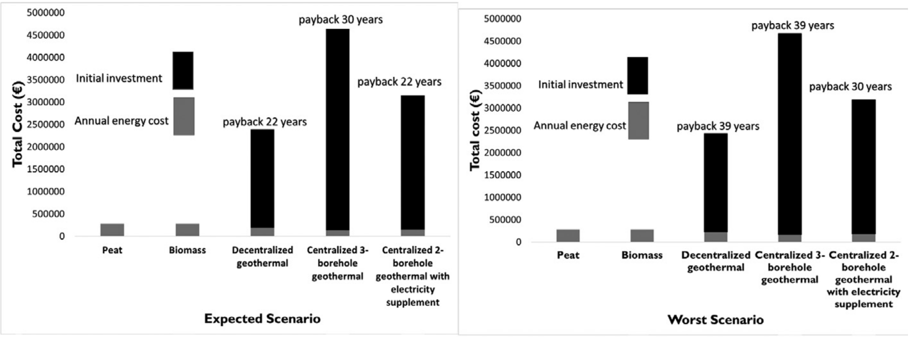


Fig. 13. Forecasts for annual heat costs based on both the expected and the worst scenarios of electricity market.

5. Discussion and conclusions

Through a direct economically comparative analysis among the proposed scenarios of MEHS, geothermal energy alone is not a feasible technology based on both the expected and the worst scenarios of electricity market, which is consistent with some of the existing literature [7,8,29]. The best strategy would be that the Olympic Training Center stays at the peat-fired boiler as long as the fixed-price contract ends in 2023. Then the option seems to be biomass from forest residue if the price of biomass stays at the current level. The key is the analysis and projections of biomass fuel prices, which is not the focus of this paper. The recent news published on July 22, 2022 by the Wood Recyclers Association warning that the prices of wood residues would go "sky-high" [47]. Such a remarkable increase of biomass prices indicates that geothermal technology can become promising alternatives to substitute the peat source. Then the innovative option of mixed centralized geothermal technology with electricity purchasing from the grid presents an economic option. Additionally, based on the expected scenario of the electricity market, the mixed geothermal and grid MEHS is feasible option with public funding of the initial investment by 30 %.

We further apply lifecycle analysis (LCA) method to investigate economic feasibility performance of these MEHS technologies. An important profitability indicator of lifecycle NPV [48] is employed that can account for all revenues, expenses, and capital costs associated with an investment cash flow. NPV compares the cash of



(a) (b)

Fig. 14. Summary of feasibility studies of innovative scenarios of MEHS based on the expected (a) and the worst (b) scenarios of electricity market.

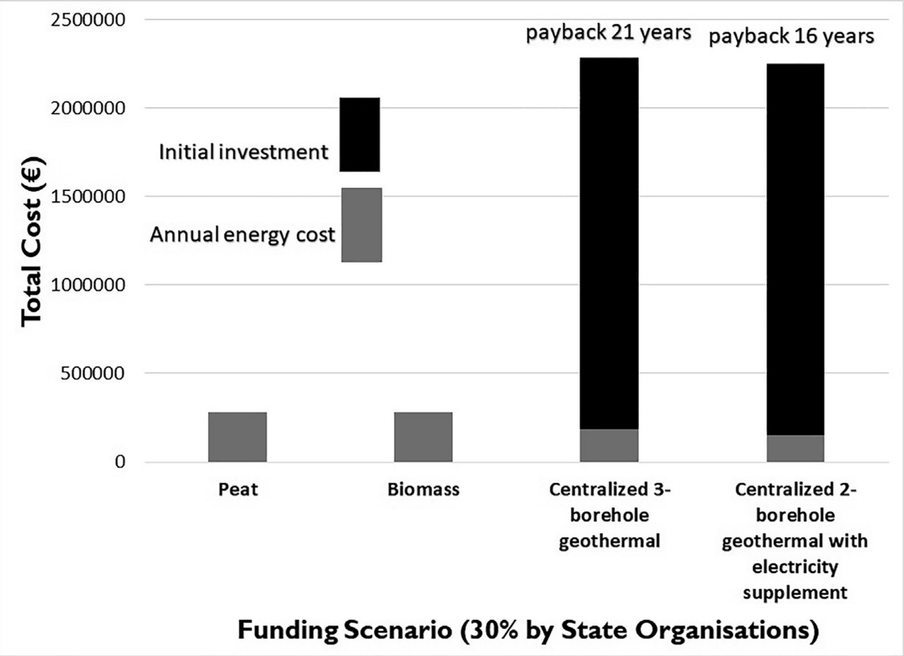


Fig. 15. Summary of feasibility studies of the mixed centralized geothermal and grid technology based on the expected scenario of electricity market.

euros to the value of the same amount of euros in the lifecycle. The cash inflow and outflow for each future year is discounted to calculate present value of the cash flow.

$$NPV = \sum_{1}^{n} \frac{NCF_n}{(1+r)^n} - IV \tag{3}$$

where

r = market capitalization rate.

n = life cycle in year.

NCF = net cash flow.

IV = investment.

Fig. 16 shows the lifecycle NPVs for the proposed scenarios of MEHS. The decentralized geothermal system requires ample land (187 shallow boreholes) which can cause major environmental impacts, however, this paper does not consider this environmental impact as an integral part the feasibility studies. Given that the NPV difference between the decentralized geothermal system and the mixed centralized geothermal and grid system is negligible, the latter MEHS is much more viable than the previous system. Additionally, we believe that deep geothermal drilling costs will gradually go down through improvements in the learning curve, although there is still little experience on deep boreholes and drilling techniques today.

The developed LCA of MEHS include different cost categories with production, operation and maintenance being the major ones. Going into detail of the cost categories, the components with rela-

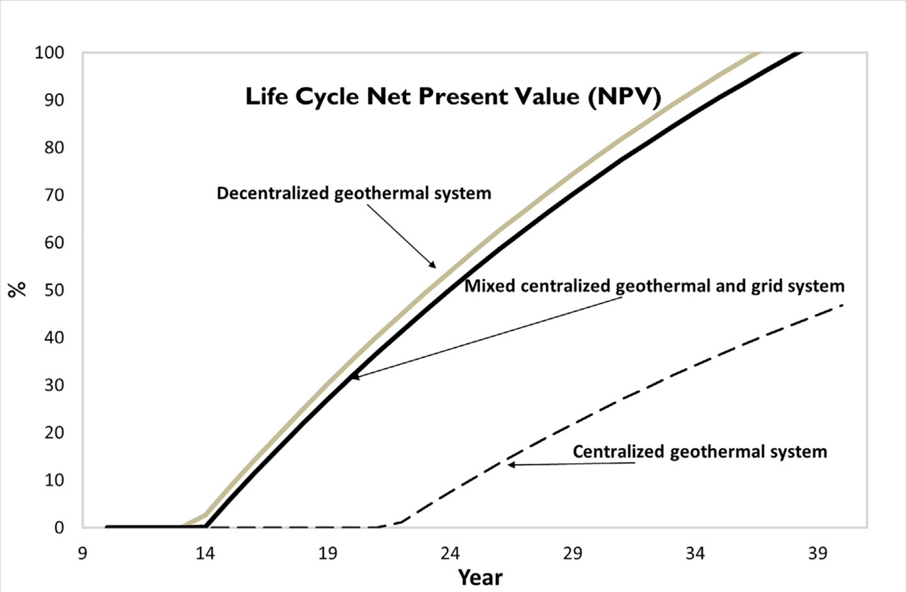


Fig. 16. Lifecycle NPV results for the proposed scenarios of MEHS.

tively high costs are module, inverter, mounting material and other electronics for PV system and heat pump for geothermal system. Since the exact cost prices were regarded as confidential business information, actual cost data are not available. Based on solar PV data reports [49,50], we calculated the total lifecycle cost as 1,6864 normalized to (€/W). This value is in line with that of roof top mounted PV system (>1MW) [51]. For a 20-year lifetime, the LCA breakdown is module (∼46 %), inverter (∼23 %), mounting material (∼23 %), and other electronics (∼8%). The operation and maintenance (O&M) cost of the PV system is estimated as 5873 € (see also [51]).

Geothermal heat pump prices are 20–40 % of the total system cost. For O&M, the compressors have a lifetime of 20–25 years. Geothermal systems should have annual maintenance to ensure proper operation (e.g. clean coils, filters, ducts, and condensate traps, no leaks and correct ground loop pressure, etc). The O&M comprises heat pump maintenance cost 140-330€/year, the costs of replacement 1785–6110 € and repairs 188–1880 €.

It should be noted that the LCA analysis applied in this study is limited to economic assessments. Examination of carbon emissions could unveil environmental impact. A carbon tax sets fee to provide an incentive to reduce emissions. However, many countries currently do not have a carbon tax at a national level. As most of the MEHS components were manufactured in China and other Asian countries, no suitable data was found for the effects of MEHS' carbon tax. The European Commission is activating the Carbon Border Adjustment Mechanism [52] in 2023 with a transition period and is going to implement it fully in the beginning of 2026. Then the carbon footprint for the imported MEHS components will be visible. In Finland, the carbon payback times of PV and geothermal systems are only a few years (e.g. one to two years).

Future work should address the above-mentioned limitations, such as an assessment of environmental impacts regarding the land requirements and carbon tax. Due to the volatility of electricity prices (e.g. the Ukraine war has triggered the biggest price shock), the proposed time series model may fail to effectively capture the unprecedented changes of the electricity market. Further improvement of the electricity market forecast methods is necessitated. Despite the limitations, we believe that this study provides a generic and comprehensive methodology and decision-making tool for the development of various RES-based MEHS and the analysis of the economic feasibility of investments in MEHS options for buildings at city and regional levels.

Data availability

Data will be made available on request.

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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