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Thermoeconomic analysis of heat and electricity prosumers in residential zero-energy buildings in Finland

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Abstract

Energy planning and management in the built environment should not limit their scope to reaching zero-energy or nearly zero-energy balances: they should aim for cost optimality as well. Only then can environmental and economic sustainability be attained. In this study, a set of energy systems that include exchange with electrical and heating grids are proposed for an existing single-family house in Finland. The simulated energy and exergy balances are quantified, as well as the levelized cost of electricity and levelized cost of heat, the simple payback period and the internal rate of return of the investment. By driving a heat pump to convert surplus electricity into heat and exporting it, an annual energy surplus of 36 kWh/m²/a is achievable, whereas by importing heat from a heating grid leads to an annual exergy surplus of 8 kWh/m²/a. However, the economic indicators are unattractive: the lowest levelized cost of electricity and simple payback period are 41 cent/kWh and 46 years respectively, while the highest internal rate of return is 3.2 %. Thus, the results indicate that reaching zero-energy balances in a cost-effective manner in single-family house under the current conditions in Finland is an arduous endeavour.

Keywords

Zero-energy buildings, prosumers, exergy balance, hybrid grids, cost optimality, thermoeconomic analysis.

Nomenclature

A	Cash flow
C	Cost
E	Energy
e	Escalation rate
I	Investment
i	Interest rate
IRR	Internal rate of return
LCOE	Levelized cost of electricity
LCOH	Levelized cost of heat
p	Price
SPP	Simple payback period
Q	Heat
X	Exergy

Sub-indices

El	Electricity
exp	Export
h	Hours
imp	Import
ini	Initial
n	Year
net	Net
O&M	Operation and maintenance
Q	Heat
repl	Replacement
salv	Salvage value
self	Self-consumption
st	Solar thermal

Abbreviations

C	Conventional
COP	Coefficient of performance
DHW	Domestic hot water
EH	Electrical heater
EPBD	Energy Performance of Buildings Directive
GSHP	Ground source heat pump
HP	Heat pump
HWST	Hot water storage tank
IRR	Internal rate of return
LCOE	Levelized cost of electricity

LCOH	Levelized cost of heat
LT	Low temperature
nZEB	Nearly zero-energy building
PV	Photovoltaic
REMM	Rational Exergy Management Model
SPP	Simple payback period
ST	Solar thermal

1. Introduction & Background

As the pursuit of sustainability continues, it has become clear that energy planning and management in the built environment should not only progress towards the net zero or nearly zero-energy balance but that it should also be reached in a cost-effective manner. Without such an economic perspective, the costs of constructing nearly zero-energy buildings (nZEBs) may outweigh the benefits, so the measures that are set in place to reduce the energy use in buildings are at risk of being ineffective. Therefore, it is crucial to determine which energy strategies lead to profitable monetary investments. Moreover, directive 2010/31/EU, the Energy Performance of Buildings Directive (EPBD), establishes that all new buildings built from the beginning of 2021 must be nearly zero-energy and cost-optimal [1]. The member states of the European Union thus have a task to find strategies that allow reaching low-energy demand by cost-optimal solutions.

These strategies are being thoroughly investigated as several researchers have analyzed the performance of energy systems and/or saving measures in nZEBs from a techno-economical point of view. Marszal & Heiselberg studied the life cycle cost of photovoltaic (PV) systems with different options for heat supply in a Danish net zero-energy building [2]. They found that while PV in combination with a heat pump (HP) is the cost-optimal combination, PV in combination with a solar HP is the most energy efficient. Evins developed a multi-level optimization process for building design that contemplates several alternatives for onsite renewable energy systems [3]. The author addresses the need to consider the operational behaviour of each component in order to balance the energy sources. In a different study, Hamdy et al. introduced a multi-objective optimization method to find cost-and-energy-optimal performance levels in nZEBs and applied the method to a single-family house in Finland [4]. They conclude that cost-optimal solutions that have low energy consumption levels can be found, particularly through the use of environmentally-friendly heating systems such as ground-source heat pumps (GSHPs). Moreover, Hirvonen et al. focused on Finnish single-

family buildings too and studied the economic potential of photovoltaic systems linked to different options for heat generation and/or supply [5]. They propose a calculation method for the levelized cost of energy (LCOE) that takes into account the market price of electricity and the variability of PV generation. With this method, energy matching and its influence on cost-optimality can be assessed.

Another area of research on cost-optimality in the built environment follows approaches that rely on establishing exergy as the basis for the economic analysis [6]. These so-called exergy-based economic methods presume that exergy should be the fundamental criterion for calculating the costs of satisfying the energy demand in a system, since it is the fraction of energy that performs the desired work or function [7]. Sangi et al. performed a thermoeconomic analysis of the heating system in a research centre located in Aachen, Germany [8]. This allowed them to identify the main sources of inefficiency and their impact on costs, as well as to identify the devices that require improvement. Akbulut et al. also followed an exergy-based approach to evaluate a heat pump–integrated wall heating system [9]. The authors observe that energy and exergy efficiencies can be similar at a component level and still significantly different for the entire system. They remark that GSHPs are noteworthy as an energy conversion technology and find that analyses of the economic and environmental impacts of irreversibility should be based on the exergy concept. Overall, exergy-based economic methods represent an insightful option for addressing energy generation, conversion and exchange processes, such as bidirectional exchange with heating grids.

Parallel to this, there is growing interest in the role of district heating systems on the road towards sustainability. In 2010, Lund et al. analysed how the energy system in Denmark could be converted to 100 % renewable energy sources [10]. Their conclusion was to supply up to 70 % of the buildings with district heating and use individual heat pumps for the rest, thus making district heating the main source of heat for the built environment. Four years later, Lund et al. proposed the way the district heating should be developed to reach the aforementioned goals, and defined the concept of *4th Generation District Heating* [11]. One of the key aspects of the 4th generation is the evolution of current heating grids into *smart thermal grids* that allow contributions from individual buildings. This does not come without a challenge, as the interaction between the grid and buildings is affected by temperature levels. To address this, it is necessary to apply tools that consider the exergy levels of the heat transfer processes in the built environment. Such a tool has

been developed by Kilkiş [12]. Through the Rational Exergy Management Model (REMM), the author aims to reduce primary energy consumption and CO₂ emissions by means of improving the match of the exergy values of the energy supply and demand. Moreover, Kilkiş applied REMM to propose energy concepts for a pilot, near net-zero exergy district in Sweden [13], and stressed the importance of exergy-aware planning.

Yet, energy quality management is not the only key aspect of the transition to smart thermal grids. Another important task is to quantify the contribution of decentralized heat supply to the smart thermal grid. Brange et al. addressed this by studying the potential of heat and electricity prosumers in one area in Malmö, Sweden [14]. By exporting excess heat from cooling processes, prosumers could cover around 50 % of the annual heat demand in the area. Even though challenges arise, such as the need for seasonal storage, this study shows that heat prosumers could become protagonists in the future energy systems. One more aspect that needs to be addressed is the economic potential. The cost assessment of bidirectional heat exchange with smart thermal grids is fundamental to ensure that such systems are viable options. Verda et al. present simple examples where thermoeconomic analysis is applied to reflect the costs of energy transfer based not only on quantity, but also on quality [15]. The authors conclude that such an analysis can provide insight during the design phase of heat networks, as well as during the operational phase.

The previous review of literature indicates some opportunities for further exploring cost-optimality in nZEBs. To the best knowledge of the authors, no dynamic studies using exergy-based economic methods have included bidirectional heat exchange with a heating grid. This has lately gained relevance as existing and upcoming construction projects in Finland allow the consumer to export and import heat to and from the heating grid [16]. While the study by Verda et al. is exergy-based, it is not dynamic and it does not analyse the performance of different generation systems, and the study by Brange et al. does not take the energy quality into account. Thus, the topic of the exergy-based economic potential of nZEBs with interconnectivity to hybrid energy grids could benefit from further investigation.

In order to address the topic, this study presents an energy- and exergy-based economic analysis of an existing nZEB. The purpose is to investigate a set of economic performance indicators for a group of energy topology options with different strategies to export surplus energy to the electrical and heating grids. Based on results from energy demand and generation models, the energy and exergy balances have been obtained.

Next, the monetary cash flows from the generation systems and energy exchange have been calculated. With this information, the economic indicators have been calculated, and their behaviour has been compared to that of the energy and exergy balances.

This paper is divided into five sections. In Section 2, the studied building is presented, along with the existing and proposed energy topologies. Section 3 explains the methodology – including the simulation tools, costs and rates assumed for the economic calculations – the equations used and the assumptions upon which the sensitivity analysis is based. Section 4 presents the results and discussion, while Section 5 draws the conclusions.

2. The building, energy topologies and energy components

This section elaborates on the built environment and energy systems studied. It includes a description of the nZEB that is the basis of this study. Moreover, it presents the existing energy topology of the building and a set of proposed variations. Finally, it describes in detail the components of the energy topologies.

2.1. Villa ISOVER

The companies ISOVER and Fortum worked on a joint project to investigate the performance of a zero-energy building. For this project, they commissioned the design and construction of a single-family house in Hyvinkää, southern Finland [17]. Its construction was completed in 2013, and the house has been occupied by a family of four since then. The building, named Villa ISOVER, adheres to and exceeds the technical regulations in the National Building Code of Finland, which establishes requirements for thermal insulation, air-tightness, ventilation, and other construction and service parameters [18]. Furthermore, the house incorporates diverse energy generation systems, namely PV panels, solar thermal (ST) collectors, and a GSHP. Some of the building's features and its measured energy demand are shown in Table 1. A monitoring system logs the outputs of the onsite generation units as well as the energy exchange with the electrical grid, the electricity and heating demand of the building, and several other variables. The data from this monitoring system allows researchers to analyze the performance of the building and its energy system, which in turn makes this dwelling a suitable option for the investigation presented in this document. Further information about the building is available in [17, 19].

Table 1 – Villa ISOVER’s features and measured energy consumption [17].

Type	Feature		Unit	Value
Planned	Dimension	Net area	m^2	175
	U-values	Walls	$W/(m^2K)$	0.09
		Roof	$W/(m^2K)$	0.06
		Floor	$W/(m^2K)$	0.09
		Windows	$W/(m^2K)$	0.76
Measured	Energy demand	Heating	$kWh/(m^2a)$	50.1
		DHW	$kWh/(m^2a)$	7.7
		Electricity	$kWh/(m^2a)$	52.8
Nominal	ST collector area		m^2	6
	CIS PV peak power		kW	9.36
	GSHP rated heat output		kW	6.3
	GSHP rated COP		-	4.51
	HWST volume		liters	750

2.2. Energy topologies

Figure 1 presents the existing energy topology of Villa ISOVER. This topology includes a PV system, a ST system and a GSHP. Bidirectional energy exchange is possible with the electrical grid. However, there is no connection to a heating grid: the ST collectors and GSHP supply their output to a hot water storage tank (HWST), which in turn delivers the heat required to cover the heating and domestic hot water (DHW) demand of the building. As this system cannot exchange heat with a grid, it does not allow the study of the effects of energy conversion and interconnectivity with hybrid energy grids.

Figure 1 – The energy topology of Villa ISOVER.

Three hypothetical energy topologies, or cases, are proposed and investigated in this article, each case with two expansion options and two subcases. The expansion options simply refer to the increased size of the generation system: expansion *PV* for a growing PV system and expansion *ST* for a growing ST system. The subcases refer to the form of the exported surplus electricity: subcases *EI* for electricity and subcases *Q* for heat. As an example, Case 1-PV-EI refers to Case 1 that features a growing PV system and the export of surplus electricity in the form of electricity, whereas Case 2-ST-Q refers to Case 2 that features a growing ST system and the export of surplus electricity in the form of heat (often called “electrical heat”). These topologies are based on those investigated in [20]. The first topology, named Case 1, is the most similar to that which exists in the building: the differences arise in the proposed subcases. In *EI* subcases, the surplus electricity is exported to the electrical grid, as in the real system. However, in *Q* subcases the surplus electricity is fed to a virtual electric heater (EH), which converts the surplus electricity into heat and delivers it to a virtual heating grid. Figure 2 shows the energy topology of Case 1. In Figures 1 to 4, the grids are the only components outside of the energy system boundary.

Figure 2 – The energy topology of Case 1.

In Case 2, the GSHP is removed, and a connection to a virtual heating grid is assumed. Furthermore, heat can be exchanged bidirectionally with this grid, and export capability is assumed for the ST system. In *EI* subcases, the surplus electricity is exported to the electrical grid, while in *Q* subcases the surplus electricity is fed to a virtual air-source heat pump, which generates heat and delivers it to the virtual heating grid. Figure 3 shows the energy topology of Case 2.

Figure 3 – The energy topology of Case 2.

In Case 3, the export capability of the ST system to a virtual heating grid is assumed and the GSHP is not removed. As in Case 1, the ST system and the GSHP supply all the heat required to cover the heating and DHW demand of the building. No heat is imported from the grid as operation of the GSHP is preferred due to its coefficient of performance (COP). In EI subcases, the surplus electricity is exported to the electrical grid, while in Q subcases the surplus electricity is fed to a virtual air-source HP, which generates heat and delivers it to the virtual heating grid. Figure 4 shows the energy topology of Case 3.

Figure 4 – The energy topology of Case 3.

2.3. Energy components

The energy generation and conversion components in this study can be split into two main categories: existing and virtual. The existing components consist of those installed in the existing building, while the virtual ones do not exist in the building and have been added for research purposes. Table 2 shows the main components used in the proposed cases and subcases.

Table 2 – The main features and energy components of the case studies.

Case	PV capacity [kWp]	ST capacity [m ²]	GSHP	Subcase	Export to electrical grid	Connection to the district heating grid			
						Export of surplus heat from ST system	Heat import from virtual grid	Export via virtual EH	Export via virtual HP
1-PV	9.4/ 10.4/ 11.4/ 12.5/ 13.5/14.6/ 15.6/16.6	6	✓	EI	✓	-	-	-	-
				Q	-	-	-	✓	-
1-ST	9.4	6/ 8/ 10/ 12/ 14/ 16/18/20	✓	EI	✓	-	-	-	-
				Q	-	-	-	✓	-
2-PV	9.4/ 10.4/ 11.4/ 12.5/ 13.5/14.6/ 15.6/16.6	6	-	EI	✓	✓	✓	-	-
				Q	-	✓	✓	-	✓
2-ST	9.4	6/ 8/ 10/ 12/ 14/ 16/18/20	-	EI	✓	✓	✓	-	-
				Q	-	✓	✓	-	✓
3-PV	9.4/ 10.4/ 11.4/ 12.5/ 13.5/14.6/ 15.6/16.6	6	✓	EI	✓	✓	-	-	-
				Q	-	✓	-	-	✓
3-ST	9.4	6/ 8/ 10/ 12/ 14/ 16/18/20	✓	EI	✓	✓	-	-	-
				Q	-	✓	-	-	✓

Existing components

As described in Subsection 2.1, the building energy topology consists of PV and ST systems, and a GSHP. Furthermore, subcases PV and ST propose increasing the size of those components in order to study the effect of increasing the generation capacity. For all the PV subcases, the PV system grows linearly from 9.4 to 16.6 kWp, whereas for all the ST subcases, the ST system grows linearly from 6 to 20 m². For each subcase, eight sizes have been calculated. The precise system sizes can be seen in Table 2. The characteristics of the GSHP are not modified: it is either present (in Case 1 and Case 3) or absent (in Case 2). For the PV and ST systems, annual degradation rates in generation performance are set at 0.5 %, based on [21] and [22].

Virtual components

To analyze the exchange capability for heat, three virtual components have been added. First and foremost, a virtual heating grid has been designed to serve both as a source and recipient of heat. Two options for

operating temperature profiles are given: the profile of a conventional heating grid in Finland and the profile of a low-temperature heating grid. The temperature ranges are shown in Table 3. The temperature profiles are modelled as one sinusoidal cycle each year, under the assumptions that the temperature of the heat-carrier fluid in the district heating lines follows the outdoor temperature and that the outdoor temperature follows a sinusoidal profile throughout the year.

Table 3 – The operating temperatures of a conventional heating grid and a low-temperature grid in °C [23, 24].

	Supply	Return
Conventional grid	65 to 115	25 to 50
Low-temperature grid	50 to 70	25 to 40

The second virtual component consists of an ideal EH with 100 % conversion efficiency, which is used to convert surplus electricity into heat and feed it to the grid. Last, the third virtual component represents a hypothetical air-source HP with a constant COP of 2.0 and an output temperature of 60 °C. This element is also meant to convert surplus electricity into heat and feed it to the grid.

For Case 2 and Case 3, the export of heat from the ST system or HP can only happen when two conditions are satisfied: the temperature of the heat-carrier fluid is over 60 °C, and the temperature of the heat-carrier fluid is at least 5 °C higher than that of the fluid in the return line of the heating grid. For export by the ST system, hot water is taken from the bottom of the HWST, part of its heat is exported to the return line of the grid and the water is then supplied to the ST collector. A minimum supply temperature to the ST collector of 55 °C after export is set to avoid a heat deficit in the HWST.

3. Methodology

The research tools and methods are presented in this section. First, the simulation environment and parameters are described. The energy and exergy analysis, and the required equations are introduced in the second subsection. In turn, the third subsection includes the costs, rates and assumptions used for the economic analysis. The fourth and last subsection presents the set of indicators selected to evaluate the economic performance of the systems.

3.1. Simulation

The building and energy topology variations were modelled in TRNSYS 17, a simulation environment for transient systems [25]. The building itself was represented as a multi-zone building with Type 56, which allows a detailed representation of the wall structures, windows, air tightness and other features of the building. The internal gains from occupants are calculated for two adults and two children based on [18], while the gains from appliances and lighting are based on measured electricity demand data from the existing building. The building model calculates the heat demand throughout one year, which is then used as input for the models that represent the energy topologies. These models, unlike the building model, run simulation periods of 25 years, as degradation of the PV and ST systems is accounted for.

For all simulations, the test reference meteorological data TRY2012 for southern Finland was used [26] as it was considered a suitable representation of the weather in this location for the desired simulation period of 25 years. The simulation time-step is 0.25 hours in all models. A small time-step was preferred as it improves simulation stability and ensures convergence, particularly for the ST collector and thermal storage models.

3.2. Energy and exergy analysis

Energy analysis

The calculations for energy generation, demand and exchange are performed by the simulation model in TRNSYS. Thus, only the equations for energy balance are hereon presented. First, the net exported electrical energy and net exported heat, E_{El} and Q respectively, are calculated as

$$E_{El} = \int_{t=1}^{t=n} [\dot{E}_{El,exp}(t) - \dot{E}_{El,imp}(t)] dt \quad (1)$$

and

$$Q = \int_{t=1}^{t=n} [\dot{Q}_{exp,st}(t) + \dot{Q}_{El,exp}(t) - \dot{Q}_{imp}(t)] dt \quad (2)$$

where $\dot{E}_{El,exp,El}$ is the exported surplus on-site electrical generation that is fed to the electrical grid, $\dot{E}_{El,imp}$ is the imported electrical power, $\dot{Q}_{exp,st}$ is the exported surplus heat generation from the ST collectors that is fed to the heating grid, $\dot{Q}_{El,exp}$ is the exported heat that is converted from the surplus on-site electrical generation and $\dot{Q}_{imp}$ is the imported heating power. The energy conversions between the electrical and

heating power have been described in Subsection 2.3. The net exported energy is the total sum of exported (positive) and imported (negative) energy in the form of electricity and heat in the building. A positive value indicates a net energy surplus, while a negative value indicates a net energy deficit.

Exergy analysis

To calculate the exergy generation, demand and exchange, a set of equations has been developed. The expressions for exergy flow in the form of electricity and heat of each component can be found in Appendix A. The net exported electrical and heating exergy, X_{El} and X_Q respectively, are calculated as

$$X_{El} = \int_{t=1}^{t=n} [\dot{X}_{E,El,exp}(t) - \dot{X}_{E,El,imp}(t)] dt \quad (3)$$

and

$$X_Q = \int_{t=1}^{t=n} [\dot{X}_{Q,exp,st}(t) + \dot{X}_{Q,El,exp}(t) - \dot{X}_{Q,imp}(t)] dt \quad (4)$$

where $\dot{X}_{E,El,exp}$, $\dot{X}_{E,El,imp}$, $\dot{X}_{Q,exp,st}$, $\dot{X}_{Q,El,exp}$ and $\dot{X}_{Q,imp}$ refer to the terms $\dot{E}_{El,exp,El}$, $\dot{E}_{El,imp}$, $\dot{Q}_{exp,st}$, $\dot{Q}_{El,exp}$ and $\dot{Q}_{imp}$ respectively, as shown in Equations (1) and (2). Since electricity has a quality factor of 1, the net electrical energy and exergy exports are equivalent. The net exported exergy is the total sum of exported (positive) and imported (negative) exergy.

3.3. Costs and rates

Generation and conversion components

The system components are split into two groups. This allows the separate calculation of the economic indicators for the electricity and heat systems. One group consists of the PV system and the components that convert surplus electricity into heat for exporting (namely the EH and HP), and the other group consists of the ST system and other sources of heat for on-site consumption (namely the GSHP and the connection to district heating). For all systems at least one price was obtained from retailers; if the price for a particular system size was not available, the price per capacity in €/kW of the closest system size was used. For precise costs and detailed information, please refer to Appendix B. Expenses other than the component prices have been considered as follows:

- Installation costs vary depending on the system and its size. For the GSHP they include the borehole and piping, while for the EH and HP they include the connection to the thermal grid. A 35 % tax deduction is included in the installation of the PV system [27].
- Operation and maintenance costs are calculated annually as 1 % and 1.5 % of the initial investment for PV systems and HPs respectively [28, 29, 30]. For the ST system, a maintenance service is considered every 10 years, based on [22].
- Replacement costs are considered every 12 and 20 years for the inverter and HPs respectively [5, 31, 32].
- The cost of connecting to the grid is included in the cases where heat is exported.

The salvage value of the HPs is taken into account in the calculation. It is assumed to start as the replacement cost of the component and end as zero, decreasing linearly during the system lifespan.

Energy prices, escalation rates and interest

The price profiles for electricity and heat follow different approaches that aim to preserve their behaviour in the market. The prices of electricity in Finland and eight other countries depend on Nord Pool, an intraday and day-ahead international energy market [33]. The prices vary each hour, depending on supply and demand. Furthermore, currently there is no well-defined trend in the average annual prices, as can be seen in Figure 5. Thus, dynamic profiles for hourly electricity market price have been created based on four years of data (from 2012 to 2015). The four-year profile is then repeated in a cyclic manner, under the effect of a price escalation rate. In addition to the market price, the retail price of electricity in Finland includes an energy tax (including VAT) and a transmission fee of 2.793 and 3.98 cent/kWh in 2015 respectively [34]. The price of heat from the heating grid is less dynamic as it is defined on a seasonal basis [35]. Therefore, for the heat price profile the price is assumed to remain constant during each year. The price at the beginning of 2016, 9.46 cent/kWh, has been taken as the starting price, and an annual escalation rate is thereon applied. Like the electricity prices, heating prices in Finland consist of several components. On average, the price for heat for single-family buildings is composed as follows: 24 % base price, 48 % energy price, 9 % energy tax and 19 % value added tax [36]. As for price differences between conventional or low-temperature grids, the prices are assumed to be the same.

The price escalation rates of electricity and heating have been calculated based on the price development from 2000 to 2015, based on the electricity retail price [37] and the average district heating prices in Finland [35]. The behaviour of heat prices has been steadier, having increased from 3.8 cent/kWh in 2000 to 8.4 cent/kWh in 2015. The trend lines shown in Figure 5 help to visualize the price escalation rates, which resemble the development of the prices. The price escalation rates of 4 % and 5 % have been calculated for electricity and heat respectively based on these trends. As for interest, a real interest rate of 3 % is used, based on [38].

Figure 5 – The historic annual average prices of heat and electricity in Finland and their trends, based on [37, 35].

Regarding the income from exported energy, in Finland the electricity exported to the electrical grid is paid at the spot market price minus a commission fee of 0.24 cent/kWh [39]. There are no historical references for the pricing of heat exported to a heating grid. A similar approach to the pricing of exported electricity is assumed: the compensation consists of the fraction of the total heat price that corresponds to the energy, 48 %, minus a commission fee assumed to be 10 % of said fraction. In total, the heat exported to the heating grid is assumed to be paid for at 43 % of the retail price. It is assumed that operation and maintenance costs of the grid that may derive from the heat export are covered by the grid operator through the commission fee and through the income from the exported energy.

3.4. Economic indicators

A set of three indicators has been used to evaluate the economic performance of the proposed systems. The simple payback period (SPP) has known limitations, yet it provides a straightforward quantity that is easy to

understand. Moreover, it is independent of inflation and escalation rates. The LCOE and levelized cost of heat (LCOH) provide an indication of the present monetary value of the generated energy. Finally, the internal rate of return (IRR) is the discount rate at which the net present value of the investment is zero. Comparing the IRR with the interest rate helps to determine whether the investment can increase the value of the invested money at a similar rate to depreciation: the higher the IRR compared to the interest rate, the more attractive the investment.

SPP is calculated as the quotient between the investment and the annual net income. In cases where a system component needs replacement, the cost is taken as half of its present price. This allows the inclusion of these expenses without introducing an interest rate. Thus, SPP is calculated as

$$SPP = \frac{I_{ini} + C_{repl}/2}{E_{exp}p_{exp} + E_{self}p_{self} - C_{O\&M}} \quad (5)$$

where E represents energy, p represents prices, I represents investments and C represents costs. For a detailed description of the terms, please refer to the Nomenclature. The term I_{ini} includes the price of components and their installation. For all cases, this includes the price of the PV and ST systems and their installation. The expenses that are specific for each case are as follows:

- Case 1 includes the cost of the GSHP, the drilling of the borehole, piping and the salvage value of the GSHP. In addition, Q subcases include the cost of the virtual EH and its connection to the heating grid.
- Case 2 includes the cost of connection to the heating grid and export by the ST collectors. In addition, Q subcases include the cost of the virtual HP, its connection to the heating grid and its salvage value.
- Case 3 includes the cost of the GSHP, the drilling of the borehole, piping, the salvage value of the GSHP and the cost of connection for export by the ST collectors. In addition, Q subcases include the cost of the virtual HP, its connection to the heating grid and its salvage value.

For precise costs, please refer to Appendix B. The LCOE and LCOH are calculated with Equation (8) and Equation (9) respectively. These equations are based on an improved methodology by Hirvonen et al. that takes into account the savings from self-consumption as well as the income from exporting energy in

dynamic energy markets [5]. By calculating these cash flows for each time step, the influence of energy matching is acknowledged. The equations for LCOE and LCOH are

$$LCOE = \frac{I_{El,ini} + \sum_{n=1}^{25} \frac{C_{El, repl, n} + C_{El, O\&M, n} - \sum_{h=1}^{8760} (E_{El, exp, n, h} p_{El, exp, n, h} (1 + e_{El})^n + Q_{El, exp, n, h} p_{Q, exp, n, h} (1 + e_Q)^n) - A_{salv, n}}{(1 + i)^n}}{\sum_{n=1}^{25} \sum_{h=1}^{8760} \frac{E_{El, self, n, h} (1 + e_E)^n}{(1 + i)^n}} \quad (6)$$

and

$$LCOH = \frac{I_{Q, ini} + \sum_{n=1}^{25} \frac{C_{Q, repl, n} + C_{Q, O\&M, n} - \sum_{h=1}^{8760} (Q_{exp, st, n, h} p_{Q, exp, n, h} (1 + e_Q)^n) - A_{salv, n}}{(1 + i)^n}}{\sum_{n=1}^{25} \sum_{h=1}^{8760} \frac{E_{Q, self, n, h} (1 + e_Q)^n}{(1 + i)^n}} \quad (7)$$

where e represents the price escalation rate, i represents the interest rate, A represents cash flow, n represents the calculation year and h represents the calculation hour. Note that the income from exported heat generated from surplus electricity is accounted for in the equation for the LCOE. Moreover, the equations have been expanded to include operation and maintenance (O&M) costs, as well as the cost of equipment replacement when required (e.g. inverter). The IRR is calculated iteratively as

$$\sum_{n=0}^{25} \left(\frac{A_n - I_{ini}}{(1 + IRR)^n} \right) = 0 \quad (8)$$

where the cash flow A_n is the monetary income minus expenses in the n^{th} year, calculated as

$$A_n = E_{exp, n} p_{exp, n} + E_{self, n} p_{self, n} - C_{O\&M, n} - C_{repl, n} + A_{salv, n}, \quad (9)$$

which includes equipment replacement and salvage values when required. The equations for SPP and IRR are based on [40, 41].

4. Results and discussion

The results from the simulations are hereon shown. The energy and exergy balances figures are presented first, followed by the economic indicators. Next, the results are discussed and further figures are shown to emphasize the key findings.

4.1. Results

4.1.1. Energy and exergy balances

The energy balances for all cases and subcases can be seen in Figure 6, while the exergy balances for Case 1, Case 2 and Case 3 can be seen in Figure 7, Figure 8 and Figure 9 respectively. In these figures, a negative balance indicates that the building consumes more energy or exergy than it exports.

Figure 6 – The energy balances of the PV (left) and ST (right) subcases as a function of PV capacity and the ST collector area respectively. Surplus electricity can be fed as electricity (EL) to the electrical grid or as heat (Q) to the heating grid.

Figure 7 – The exergy balances in Case 1 of the PV (left) and ST (right) subcases as a function of PV capacity and the ST collector area respectively. Surplus electricity can be fed as electricity (EL) to the electrical grid or as heat (Q) to the conventional (C) or low-temperature (LT) heating grid.

Figure 8 – The exergy balances in Case 2 for the PV (left) and ST (right) subcases as a function of PV capacity and the ST collector area respectively. Surplus electricity can be fed as electricity (EL) to the electrical grid or as heat (Q) to the conventional (C) or low-temperature (LT) heating grid, along with surplus heat from the ST system.

Figure 9 – The exergy balances in Case 3 of the PV (left) and ST (right) subcases as a function of PV capacity and the ST collector area respectively. Surplus electricity can be fed as electricity (EL) to the electrical grid or as heat (Q) to the conventional (C) or low-temperature (LT) heating grid, along with surplus heat from the ST system.

4.1.2. Economic indicators

The LCOE and LCOH, SPP and IRR for all cases and subcases can be seen in Figure 10, Figure 11 and Figure 12. The slope changes are caused by price changes as system sizes increase.

Figure 10 – The LCOE (left) and LCOH (right) as a function of PV capacity and ST collector area respectively. Surplus electricity can be fed as electricity (EI) to the electrical grid or as heat (Q) to the heating grid. Average retail electricity (left) and heating (right) prices in 2015 are shown for comparison.

Figure 11 – The SPP of PV subcases (left) and ST subcases (right) as a function of PV capacity and the ST collector area respectively. Surplus electricity can be fed as electricity (EI) to the electrical grid or as heat (Q) to the heating grid.

Figure 12 – The IRR of PV subcases (left) and ST subcases (right) as a function of PV capacity and the ST collector area respectively. Surplus electricity can be fed as electricity (EI) to the electrical grid or as heat (Q) to the heating grid.

4.2. Discussion

4.2.1. Energy and exergy balances

The energy topology of the building has a notable effect on the energy balance, as seen in Figure 6. The benefit of converting surplus electricity into heat by means of a HP is shown in said figure, where Case 3-PV-Q and Case 2-PV-Q have the highest energy surplus, ranging from 36 to 105 kWh/(m² a) and from 2 to 71 kWh/(m² a) respectively. The presence of the GSHP in Case 3 decreases the heating energy import and thus allows Case 3-PV-Q to yield the best results in terms of energy exchange with the grids. The lowest values are obtained in Case 2-PV-EI, ranging from -37 to -2 kWh/(m² a). The ranking of the energy balances of PV subcases is similar to the ranking of PV subcases: the highest values are obtained in Case 3-ST-Q, ranging from 36 to 59 kWh/(m² a), and the lowest values are obtained in Case 2-ST-EI, ranging from -37 to -13 kWh/(m² a).

By observing the exergy balances, three particular conditions can be deduced. One condition is that, in all cases, exporting the surplus electricity to the electrical grid leads to a higher exergy balance than converting it to heat and feeding it to the heating grid. For example, subcases PV-EI have net exported exergy values ranging from -7 to 44 kWh/(m² a), whereas values subcases PV-Q range from -41 to -11 kWh/(m² a). The second condition is that, in all cases, converting the surplus electricity into heat and feeding it to the heating grid leads to exergy deficit, with the highest value being -11 kWh/(m² a). The third condition is that importing energy from the heating grid, as in Case 2, leads to the highest exergy surplus, ranging from 8 to 44 kWh/(m² a) for Case 2-PV-EI-LT and from 8 to 13 kWh/(m² a) for Case 2-ST-EI-LT. These three conditions indicate a stark contrast between the energy and exergy performance of the proposed system

topologies. The first and second conditions are a consequence of using high-quality energy, in the form of electricity, to generate low-quality energy, in the form of heat. While this can be beneficial to the energy balance, it is severely detrimental to the exergy balance. Moreover, the third condition reinforces this as it shows that importing low-quality energy to cover the low-quality energy demand of the building (heating and DHW) is more beneficial for the exergy balance than operating HPs. As an example, compare the exergy balances of Case 1-PV-El and Case 3-PV-El against Case 2-PV-El. The three systems have the same PV system, but in Case 2-PV-El the building imports heat from the heating grid. This leads to a net exported exergy that is 15 kWh/(m² a) higher than those of Case 1-PV-El and Case 3-PV-El.

Based on the preceding analysis of the energy and exergy balances, we identify a pair of competing strategies: if the system is designed to reach a higher energy surplus, the exergy balance is compromised, whereas if the system is designed to reach a higher exergy surplus, the energy balance is compromised. For example, take Case 3-PV-Q as a system designed to reach a high energy surplus and Case 3-PV-El as a system designed to reach a high exergy surplus – Case 3-PV-Q reaches 38 to 72 kWh/(m² a) higher net exported energy but Case 3-PV-El reaches 27 to 51 kWh/(m² a) higher net exported exergy.

Finally, the results show a 3 to 4 kWh/(m² a) higher net exported exergy in Case 2 if the system is connected to a low-temperature heating grid instead of a conventional one. This difference is small because the control strategy for heat export undermines the role of the temperature level of the district heating network. The HP and ST system are limited to exporting to the return line of the heating grid and only when the line temperature is at 55°C or below. Thus, there are no time periods when export is only possible to the conventional grid or to the low-temperature grid: if export is possible to one, it is possible to the other.

4.2.2. Economic indicators

Three types of indicators have been calculated: the LCOE and LCOH, SPP, and IRR. The results show different behaviours for the proposed systems.

The SPP curves give insight into several aspects of the energy systems. First and foremost, the SPP for the PV and ST systems range from 54 to 116 years and from 46 to 64 years respectively. Thus, all the calculated SPP are longer than the typical lifespans of PV and ST systems, which range between 20 and 25 years. Thus,

none of the systems may be expected to render a payback under the defined conditions. Next, it can be noticed that most ST subcases have shorter SPP than the PV subcases. This suggests that the annual income from ST subcases can cover a larger proportion of its initial investment than the PV subcases can. Another aspect is that in most cases the SPP increases as the installed capacity increases, except for Case 2-PV-Q and Case 3-PV-Q, where SPP reduces by approximately nine years. These two cases benefit from the COP of the HP and thus receive more income from the export of electrical heat as the installed capacity of the PV system increases.

Regarding the LCOE and LCOH, the results for all the system topologies are higher than the historic energy prices seen in Figure 5. Furthermore, the levelized costs increase as the installed capacity increases. Regarding the LCOE, the lowest values are obtained for Case 3-PV-Q, ranging from 40.8 to 45.2 cent/kWh, while the highest values are obtained for Case 2-PV-EI, ranging from 50.9 to 80.3 cent/kWh. Overall, as size increases, Q subcases give lower values of the LCOE than EI subcases. Thus, for larger systems, investing in the conversion of surplus electricity to heat gives lower values of the LCOE. Another significant result is that the LCOH is lower for both cases where heat is obtained through a GSHP instead of importing it from the grid: the LCOH for Case 1-ST and Case 3-ST ranges from 98.3 to 162.8 cent/kWh, while the LCOH for Case 2-ST ranges from 167.1 to 255.7 cent/kWh. This indicates that while the costs of the GSHP are higher than the cost of connecting to the heating grid, they are offset by the savings in heat import from the grid. This is in line with the results from Hamdy et al. [4] and Mohamed et al. [29], who also studied the Finnish built environment. Overall none of the topologies, including the one existing in the building, led to levelized costs on a par with the current energy prices.

The IRR curves give further indications of the economic performance of the systems. Regarding the PV subcases, it is notable that all of them have negative IRR values (i.e. the systems are attractive if the currency value increases with time) ranging from -0.1 % to -5.2 %, with Case 2-PV-Q and Case 3-PV-Q yielding almost identical results. This particular fact indicates that the presence or absence of the GSHP has little influence on the use of on-site generation from the PV system. In other words, electricity from the PV system is rarely used to operate the GSHP. This is a consequence of their contrasting seasonal operation: PV generation mostly takes place during the summer, when demand for heat from the GSHP is low. Notably, for

IRR all Q subcases show higher values than El subcases, ranging from -3.7 % to -0.1 % for the former and from -5.2 % to -4 % for the latter. It should also be noticed that Case 1-ST and Case 3-ST are the only ones with positive IRR, reaching 3.2 %. Moreover, the highest IRR is obtained precisely for the system that is installed in Villa ISOVER: Case 1-ST with 6 m².

4.2.3. Sensitivity analysis

The results shown and discussed are based on conditions and assumptions particular to the Finnish context, and the influence of several of them on the economic performance merits further testing. Thus, this subsection presents a sensitivity analysis on the export price of electricity, PV installed capacity, the export price of heat and the export price profile for heat export.

The low export price of surplus electricity in Finland leads to low economic attractiveness of large onsite electricity generation capacity. The influence of higher export prices is studied by implementing a fictitious feed-in tariff, designed as 1 cent/kWh increments to the actual export price. Figure 13 shows the SPP of Case 3-PV-El with 11.4 kWp of PV installed capacity – the system size that leads to a net zero energy balance – and lower PV capacities under feed-in tariffs from 0 to 10 cent/kWh. It can be seen that the SPP is highly sensitive to increments in the export price of electricity, yet the sensitivity decreases as feed-in tariffs increase: while the first cent causes a drop of 26 years in the SPP for the 11.4 kWp system, increasing the feed-in tariff from 9 to 10 cents only reduces the SPP by 2 years. This underlines the strong impact that the export price of electricity has on the economic appeal of a system, and that relatively minor support schemes – such as a 1 cent/kWh feed-in tariff – can offer significant improvement. A second observation from Figure 13 is that smaller PV systems have shorter SPP when feed-in tariffs are low or non-existent, whereas larger PV systems have shorter SPP when feed-in tariffs are high. For example, the SPP of the 4.2 kW system is roughly 15 years shorter than the SPP of the 11.4 kW system when there is no feed-in tariff, but with a feed-in tariff of EUR cent 2/kWh the SPP of both systems is virtually the same; from that point on, the 11.4 kW has a shorter SPP. This underlines the influence that self-consumption has in the economic performance of PV systems when electricity export prices are low: reducing import from the grid is more profitable than exporting electricity. The effect of self-consumption is further explored in Section 4.2.4.

Figure 13 – The SPP of Case 3-PV-El with a net-zero energy balance under several feed-in tariffs for different PV installed capacities.

As for the price of heat exported to the grid, it is pertinent to evaluate the effect of two assumptions, namely (i) the ratio of the export price versus the retail price of heat, and (ii) a constant heat export price throughout the year. Thus, the SPP of Case 3-PV-Q with 9.4 kWp of PV installed capacity – the lowest system size studied here – is recalculated under ratios ranging from 0.1 to 1 and under three different price profiles: constant, seasonal and dynamic. The constant profile assumes a constant price throughout the year, as implemented by the majority of the grid operators in Finland. It consists of a base price of 3.22 cent/kWh plus an energy price of 6.36 cent/kWh. The seasonal profile assumes different price levels depending on the season and is offered by a few grid operators in the country. It consists of the same base price, 3.22 cent/kWh, plus an energy price of 6.91 cent/kWh in January, February, March, November and December, or of 5.39 cent/kWh during other months. The constant and seasonal prices in this sensitivity analysis are those offered by Leppäkosken Lämpö Oy, Nokia, as this operator offers both pricing schemes and its prices are in close agreement with the national average [42]. The dynamic profile correlates price with outdoor temperatures, that represents a pricing system in low-temperature district heating grids, although this is not a current practice in Finland. It is assumed to consist of the same base price as the other profiles, plus a dynamic calculation for the energy price. The dynamic heat export price is calculated based on the prices by Leppäkosken Lämpö Oy, Nokia, as follows:

$$\text{For } T_{out} \geq 5 \text{ }^{\circ}\text{C:} \quad p_{Q,exp,dyn} = 3.22 + 5.39$$

$$\text{For } T_{out} < 5 \text{ }^{\circ}\text{C:} \quad p_{Q,exp,dyn} = 3.22 + 5.39 + (5 - T_{out}) * \frac{6.91-5.39}{10}$$

where the low and high prices are assumed to correspond to T_{out} of 5 and -5 °C, respectively. Figure 14 shows the SPP for Case 3-PV-Q under different export price ratios and the aforementioned pricing systems. There are two main deductions from the results. First, the ratio has a strong impact on the SPP, and can be determining to the economic feasibility of the system. Second, the constant price is the most beneficial for heat export, and there is virtually no difference in the SPP between the seasonal and dynamic profiles. This is a consequence of the seasonal behaviour of the generation system, as most of the surplus electricity generation – and thus heat export – takes place during the warm season when prices are lower. The seasonal and dynamic profiles offer almost identical results due to the assumption that for outdoor temperatures above 5 °C both profiles have the same price. Notably, compared to the constant price, the seasonal and dynamic price profiles would increase the annual cost of heat import in Case 2-PV-El only by 3.4 % and 3.1 % respectively. This indicates that the pricing strategy has a stronger influence on heat export than it does on heat import. Table 4 shows the LCOH for Case 2-PV and Case 3-PV with 9.4 kWp PV and 6 m² ST under different district heating pricing strategies and heat export price ratios. It can be seen that the effect of the pricing strategy is more significant when the heat demand is covered by district heating, as in Case 2, than when a GSHP is present, as in Case 3. For Case 2-PV, the LCOH under seasonal and dynamic pricing increases between 7 % to 11 % compared to the LCOH under constant heating prices. In comparison, the LCOH of Case 3-PV shows limited difference based on the pricing strategy. Further, it can be seen that the LCOH of Case 3-PV is lower than the LCOH of Case 2-PV regardless of the pricing strategy and heat export price ratio; this supports the economic benefit of investing in a GSHP compared to connecting to the heating grid.

Figure 14 – The SPP of Case 3-PV-Q with 9.4 kWp of PV installed capacity under different heat export price ratios and constant, seasonal or dynamic pricing systems.

Table 4 – The LCOH of Case 2-PV and Case 3-PV with 9.4 kWp PV and 6 m² ST under different district heating pricing strategies and heat export price ratios.

Case	Pricing strategy	LCOH [EUR cent/kWh]		
		Ratio = 0.1	Ratio = 0.5	Ratio = 1
Case 2-PV	Constant	162.5	147.3	128.2
	Seasonal	174.8	160.1	141.7
	Dynamic	175.7	160.9	142.4
Case 3-PV	Constant	104.1	99.7	94.2
	Seasonal	102.8	98.9	94.0
	Dynamic	103.7	99.7	94.8

The sensitivity analysis indicates that the economic performance of the proposed systems can be strongly influenced by the export prices of electricity and heat. This is particularly important for the latter, as the prices used in this study rely on assumptions. Moreover, investigation could provide deeper insight into the dependence of cost-optimality on other parameters such as the escalation and interest rates. Further, the influence of the O&M costs is notable. As an example, the 9.4 kW PV system has annual O&M costs of €175, while savings from energy self-consumption are €128. Thus, these expenses have a strong impact on cost-optimality. If they were not accounted for, the LCOE for Case 3-PV-Q, which had the lowest values, would drop from 40.8 to 30.3 cent/kWh – a reduction of 25 %.

4.2.4. Overall performance

The balances and indicators having been analysed separately, their performances will hereon be compared. First and most evident is the overall contrast of their behaviour with respect to installed capacity. The LCOE and IRR of the cases that lead to the highest energy and exergy surplus can be seen in Figure 15. The energy and exergy surplus increase as the installed capacities increase, while the economic indicators mostly show detrimental trends as the installed capacities increase. This shows that increasing the system size will most likely not provide better economic results under the context of this study. Notable exceptions of this trend are Case 2-PV-Q and Case 3-PV-Q: for these cases as the installed capacity increases, the SPP decreases and the IRR increases. Yet, the LCOE increases and the economic results obtained do not represent desirable investments.

Figure 15 – The LCOE and IRR of the cases with the highest energy (left) and exergy (right) surplus. The energy surplus (left) consists entirely of heat while the exergy surplus (right) consists almost entirely of electricity (>99 %).

One reason for the contrasting behaviour between balances and economic indicators is self-consumption. While the capacity of the generation systems has been increased, the energy demand from the building has remained constant. As an example, Figure 16 shows the energy self-consumption and export from the PV generation, and the LCOE for Case 1-PV-EI: as expected, with increasing installed capacity there is increased generation and export. However, the installed capacity has little influence over the amount of energy self-consumption. Thus, as the system size increases, the self-consumption of on-site generated energy decreases from 15 % to 10 %. Since the price of energy export is roughly one third of the price of imported electricity and roughly one half of the price of imported heat, higher levels of self-consumption are more beneficial to economic performance than the relatively lower investment costs as installed capacity increases.

Figure 16 – Energy self-consumption and export from PV generation and LCOE for Case 1-PV-EI.

A notable characteristic is that Case 3-PV-Q, which benefits from the use of two HPs, has the highest energy surplus and also the best cost-optimality according to the economic indicators. This highlights two points: investing in two HPs can improve cost-optimality and prioritizing energy over exergy leads to better economic results. The first point indicates that the COP of a HP could bring enough income from exported heat to offset the increased investment and O&M costs, whereas the second point underlines the decoupling between energy quality and energy export prices. The behaviour of the economic indicators shows that smaller systems could lead to more attractive investments. Also, Case 3-PV-Q shows a significant surplus at the smallest capacity investigated. This suggests that the net-zero energy balance could be reached with that topology using a smaller PV installed capacity, and this might also bring the system closer to cost-optimality. Further investigation could confirm this.

The effect of electrical storage has not been investigated as its presence is detrimental for the energy and exergy balances due to efficiency losses, while requiring an additional investment. Nevertheless, with the decreasing trend in electrical storage prices and increasing levels of market penetration, the influence of this component could also be the basis for future investigations.

5. Conclusions

The energy and exergy balances of a nZEB in Finland have been studied, based on variations of its energy system. Moreover, the economic feasibility of these system variations has been investigated. Both the zero-energy and zero-exergy balances could be reached with the proposed systems. Yet, it has been found that the systems designed to increase the energy surplus are detrimental for the exergy balance, while the systems designed to increase the exergy surplus are detrimental for the energy balance. Differences of 38 to 72 kWh/(m² a) in net exported energy or 27 to 51 kWh/(m² a) in net exported exergy may arise depending on the chosen strategy. Therefore, with the proposed energy topologies, a compromise must be made between energy and exergy.

The calculated economic indicators are not encouraging. The system with the best combination of energy surplus and economic indicators has an SPP of 56 years, an LCOE of 40.8 cent/kWh and an IRR of -0.3 %, with an energy surplus of 36 kWh/(m² a). This is achieved in Case 3-PV-Q, which benefits from the COP of a GSHP and a virtual HP. The system with the best combination of exergy surplus and economic indicators

has an SPP of 98 years, an LCOE of 50.9 cent/kWh and an IRR of -4.4 %, with an exergy surplus of 8 kWh/(m² a). This is achieved in Case 2-PV-El, where the GSHP was replaced with a connection to the district heating grid and surplus electricity is exported to the electrical grid. These were the best economic results obtained for systems that reach or surpass the zero-energy and zero-exergy balance.

Thus, a notable finding of this study is the difficulty of reaching zero-energy balances in a cost-effective manner in single-family houses in Finland. With no feed-in tariffs available for the residential-scale generation systems, the relatively low retail prices of electricity in the country make PV systems economically unattractive. The 45 % tax deduction on installation costs represents an approximately 11 % reduction in the initial investment, which is hardly determining. Moreover, single-family buildings typically have low occupancy rates when PV generation is high. Therefore, most of the generation is exported as surplus to the electrical grid. In countries where net-metering is established, this would have little influence in monetary savings, yet in Finland this means losing roughly two thirds of the savings for electricity and roughly half of the savings for heat. Further, as shown by the sensitivity analysis, feed-in tariffs can lower the SPP of the system by up to 26 years per EUR cent of feed-in tariff. This indicates a strong potential to increase the economic performance of onsite electricity generation and its export to the grid. For heat, the export price is based on the assumption that the user would receive a fraction of the price that corresponds to the energy and, as shown by the sensitivity analysis, this parameter is determining for the economic appeal of heat export. Moreover, the pricing strategy of district heating also affects the SPP of heat-exporting systems. If the prices of district heating – and subsequently the prices of heat export – are lower in summer or when outdoor temperatures are high, the SPP of the system will be longer, as most of the energy surplus takes place during the warm season. Therefore, economic calculations for a heat and electricity prosumer may be considered valid exclusively under the given context, and one-fits-all solutions should be avoided.

Regarding the behaviour of energy and exergy balances and the economic indicators, the results do not indicate a clear path towards cost effectiveness, yet they hint that export of heat via an HP is more profitable than exporting surplus electricity to the electrical grid. Nevertheless, the results obtained in this investigation are limited to a set of predefined system sizes and configurations: deeper insight into this relation could be

realized through a multi-objective optimization study. Such an investigation could find alternative system configurations and capacities which are more encouraging from an economic perspective.

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Appendix A: The exergy calculation of the system's components

Electricity

The exergy flow from generation by the PV panels, $\dot{X}_{El,gen,PV}$, is calculated as

$$\dot{X}_{El,gen,PV} = \dot{E}_{El,gen,PV} \quad (A.1)$$

assuming that electricity has an exergy factor of one, where $\dot{E}_{El,gen,PV}$ is the electrical power generation by the PV panels. Similarly, the assumption is applied for exported electricity when it is not converted to other forms of energy, $\dot{X}_{E,El,exp}$. That is,

$$\dot{X}_{E,El,exp} = \dot{E}_{El,exp} \quad (A.2)$$

where $\dot{E}_{El,exp}$ is the electrical power exported as electricity. For surplus electricity exported to the heating grid via the ideal EH, the exported exergy flow, $\dot{X}_{Q,El,exp}$, is calculated as

$$\dot{X}_{Q,El,exp} = \dot{Q}_{El,exp} * \left(1 - \frac{T_0}{T_{line}}\right), \quad (A.3)$$

which is the Carnot efficiency for exergy transfer as heat, where $\dot{Q}_{El,exp}$ is the electrical power converted to heat and exported and T_0 and T_{line} are the reference and district heating line temperatures in K respectively. For surplus electricity exported to the heating grid via the hypothetical HP, the exported exergy, $\dot{X}_{Q,El,exp}$, is calculated as

$$\dot{X}_{Q,El,exp} = \dot{Q}_{El,exp} * COP * \left(1 - \frac{T_0}{T_{HP}}\right) \quad (A.4)$$

where COP is the coefficient of performance of the hypothetical HP and T_{HP} is its output temperature.

Heat

The exergy flow generation by the ST collector, $\dot{X}_{ST}$, ground heat exchanger, $\dot{X}_{ghx}$, and GSHP, $\dot{X}_{GSHP}$, are calculated as

$$\dot{X}_{st} = \frac{\dot{Q}_{st}}{T_{out,ST} - T_{in,ST}} \left[(T_{out,ST} - T_{in,ST}) - T_0 * \ln \left(\frac{T_{out,ST}}{T_{in,ST}} \right) \right], \quad (A.5)$$

$$\dot{X}_{ghx} = \frac{\dot{Q}_{ghx}}{T_{out,ghx} - T_{in,ghx}} \left[(T_{out,ghx} - T_{in,ghx}) - T_0 * \ln \left(\frac{T_{out,ghx}}{T_{in,ghx}} \right) \right], \quad (A.6)$$

and

$$\dot{X}_{GSHP} = \frac{\dot{Q}_{GSHP}}{T_{out,GSHP} - T_{in,GSHP}} \left[(T_{out,GSHP} - T_{in,GSHP}) - T_0 * \ln \left(\frac{T_{out,GSHP}}{T_{in,GSHP}} \right) \right] \quad (A.7)$$

where $\dot{Q}_{st}$, $\dot{Q}_{ghx}$ and $\dot{Q}_{GSHP}$ are heat power generated by the ST collector, ground heat exchanger and GSHP respectively. In Equation (A.7), $T_{in,GSHP}$ and $T_{out,GSHP}$ refer to the inlet and outlet temperatures of water on the condenser side of the GSHP. Where heat is exported to the heating grid by the HP, the exergy flow, $\dot{X}_{exp,HP}$, is calculated as

$$\dot{X}_{exp,HP} = \frac{\dot{Q}_{exp,HP}}{T_{HP} - T_{line}} \left[(T_{HP} - T_{line}) - T_0 * \ln \left(\frac{T_{HP}}{T_{line}} \right) \right] \quad (A.8)$$

where $\dot{Q}_{exp,HP}$ is the exported heat flow from the HP and T_{HP} is its output temperature in K . For heat export by the ST collector, the exergy flow $\dot{X}_{Q,exp,st}$ is calculated as

$$\dot{X}_{sQ,exp,st} = \frac{\dot{Q}_{exp,st}}{T_{exp,st} - \max[T_{line}; 328]} \left[(T_{exp,st} - \max[T_{line}; 328]) - T_0 * \ln \left(\frac{T_{exp,st}}{\max[T_{line}; 328]} \right) \right] \quad (A.9)$$

where $\dot{Q}_{exp,st}$ represents the exported heat flow and $T_{exp,st}$ is the temperature in K at which the export by the ST collector takes place. A minimum of 55 °C (328 K) for the return temperature to the ST collector is defined to avoid cooling down the HWST. The exergy supplied for floor heating, $\dot{X}_{FH}$, and domestic hot water, $\dot{X}_{DHW}$, are calculated as

$$\dot{X}_{FH} = \dot{Q}_{FH} * \left(1 - \frac{T_0}{T_{FH}}\right) \quad (A.10)$$

and

$$\dot{X}_{DHW} = \dot{Q}_{DHW} * \left(1 - \frac{T_0}{T_{DHW}}\right) \quad (A.11)$$

where T_{FH} is the supply temperature to the floor heating system as per manufacturer guidelines and T_{DHW} is the supply temperature for DHW, with a value of 55 °C as per regulations. The exergy demand for ventilation $\dot{X}_{vent}$ is calculated as

$$\dot{X}_{vent} = \frac{\dot{Q}_{vent}}{T_{sup,vent} - T_{in,vent}} \left[(T_{sup,vent} - T_{in,vent}) - T_0 * \ln \left(\frac{T_{sup,vent}}{T_{in,vent}} \right) \right] \quad (A.11)$$

where $T_{sup,vent}$ is the temperature of the air supplied to the heated volume, with a temperature of 18 °C as per regulations, and $T_{in,vent}$ is the temperature of the air incoming to the ventilation system after the heat recovery system.

Appendix B: Costs

This appendix contains the prices used in the calculation of the economic indicators. No references were found regarding the cost of connecting the virtual EH, virtual HP or the GSHP to the district heating grid. Therefore, the connection costs have been assumed as follows:

- In Case 1 the connection of the virtual EH to the district heating grid costs 50 % of a typical connection.
- In Case 2 and Case 3 it is 150 % of a typical connection's cost as multiple connections are required.

Table B.1: Costs related to the PV system and surplus electricity exchange with the grid. All quantities in € unless specified.

PV	System capacity [kW]	9.4	10.4	11.4	12.5	13.5	14.6	15.6	16.6	Ref
	Panels	14910	16567	18223	19880	21537	23193	24850	26507	[39]
	Installation	4700	5222	5744	6267	6789	7311	7833	8356	[39]
	Inverter replacement	2464	3119	3119	3119	3619	3619	4654	4791	[43]
	O&M ^a	180	200	220	240	259	279	299	319	[28]
Virtual EH	System capacity [kW]	10	10	10	11.5	11.5	13	14.5	16	-
	Component	250	250	250	302	302	354	406	458	[44]
	Installation	1550	1550	1550	1550	1550	1550	1550	1550	-
Virtual HP	System capacity [kW]	8	8	8	8	12	12	12	12	-
	Component	3675	3675	3675	3675	4555	4555	4555	4555	[45]
	Control	650	650	650	650	650	650	650	650	[46]
	Installation	2325	2325	2325	2325	2325	2325	2325	2325	-
	O&M ^b	90	90	90	90	103	103	103	103	[29]
	Replacement ^c	4837	4837	4837	4837	5717	5717	5717	5717	-

^aPV O&M is 1 % of initial cost [28].

^bHP O&M is 1.5 % of initial cost (not including a control) [29].

^cHP replacement includes the HP and only half of the initial installation and connection cost as no digging would be required.

Table B.2: Costs related to the ST system and surplus heat exchange with the grid. All quantities in € unless specified.

ST	System capacity [m ²]	6	8	10	12	14	16	18	20	Ref
	Panels	2990	3460	5280	6055	6740	7425	8353	9281	[47]
	Installation ^a	2990	3460	5280	6055	6740	7425	8353	9281	-
	O&M ^b	895	1193	1492	1790	2088	2387	2685	2983	[22]
GSHP	System capacity [kW]	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	-
	System	5459	5459	5459	5459	5459	5459	5459	5459	[48]
	Borehole	4282	4282	4282	4282	4282	4282	4282	4282	[29]
	Piping	2625	2625	2625	2625	2625	2625	2625	2625	[29]
	O&M ^c	185	185	185	185	185	185	185	185	[29]
	Replacement	5459	5459	5459	5459	5459	5459	5459	5459	[48]
Heating grid	Connection	2325	2325	2325	2325	2325	2325	2325	2325	[35]

^aST installation prices are assumed to be 50 % of the initial investment.

^bST O&M is 1000 USD for the base case and increases linearly.

^cGSHP O&M is 1.5 % of the initial investment.