

Challenges in reaching positive energy building level in apartment buildings in the Nordic climate: A techno-economic analysis



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ABSTRACT

Buildings consume significant amount of final energy and they emit large amount of CO₂ emissions. To address this issue, nearly zero energy buildings is becoming a common in many countries, while research is advancing towards the positive energy building (PEB) target by utilizing renewable energy that can support reducing the emissions from the building stock. The aim of this study, is to design and model a renewable-based energy system for a real demo apartment building in Nordics (Finland) in order to be a PEB, by exceeding the building's heating, cooling and plug load demands. The novelty of this study is to assesses the fulfillment of the PEB level in cold climate, by simulating various technologies (such as photovoltaic-thermal (PVT) system, heat pump (HP), wind turbines, seasonal thermal energy storage etc.) their integration with the building, its controls strategies, types of load included in the energy balance and definition of building boundaries across which the balance is calculated. TRNSYS simulation software is mainly used for dynamic simulation of the energy system. The electricity import and export, the life cycle cost (LCC), and the onsite energy matching factors are calculated to estimate the performance of the proposed system. In addition, the challenges related to the building's limited physical boundary are discussed. The results of this study shows that, if all the demands are included, i.e. heating, cooling and plug loads, then it is difficult to reach the PEB level. In this case, the investment cost in the energy system is around 47–62% of the LCC and the rest is the operational cost. On the other hand, the PEB level is relatively easier to achieve if the plug loads are excluded, then the investment cost is around 88–100% of the LCC and there can be positive cash flow due to larger energy export than import. The PEB level is possible to be achieved when all the demands are included if the building boundary is extended to a virtual boundary outside its physical boundary that allows the addition of more renewable generations or by changing the building's shape that allows the more installations of renewables on the roof. In this scenario, the investment cost on the energy system is around 62–91% of the LCC. Compared to the building cost, the energy system cost is generally low, i.e. around 1.2–4.3% of the building cost. It can be concluded that in the Nordic conditions, it is difficult to reach the PEB level for the buildings in urban areas if the all the building's energy demands are included. Renewable energy generations, such as additional PVT and wind turbines, are needed to be installed in an extended (virtual) boundary of the building if the PEB criterion has to be met when considering all the energy demands. Investment cost of the renewable energy system is low compared to the building's cost, therefore, such renewable-based solutions can be provided with small additional cost, along with the new building's cost, so that PEB and carbon neutrality targets can be achieved.

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1. Introduction

The increase in the energy consumption, the intensification of global warming and policies to reduce the need of fossil fuels have created interest to shift towards sustainable energy sources. The 2015 Paris Agreement has put more emphasis on international

efforts to reduce carbon dioxide (CO₂) emissions from buildings and the energy sector [1]. With the plans to increase the share of the RES by 32% in the European Union (EU) by 2030 [2] and to further reduce CO₂ emissions by 80% by 2050 [3], it is expected that the share of RES will increase on a yearly basis. An important sector that contributes significantly towards climate change and global warming is the building sector. Buildings account for 30–40% of global final energy consumption [4] and nearly 40% of the global CO₂ emissions. In the last decade, policies such as the Directive

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on Energy Performance of Buildings (EPBD) have been introduced to address the issue, aiming to decarbonize the building stock by 2050 and to reach net zero energy building (Net ZEB) or nearly zero energy buildings (NZEBS) [5]. With respect to the Net Zero Energy Building (Net ZEB) concept, a comprehensive work was conducted in the international collaboration joint project IEA SHC Task 40/EBC Annex 52 Net Zero Energy Solar Buildings (2008–2013) [6], which covered different aspects within its four subtasks: Definitions and Large-Scale Implications, Design Process Tools, Advanced Building Design and Case studies, and Dissemination. In accordance with that work, it can be concluded that a net zero energy building (Net ZEB) is an energy efficient grid-connected building that reaches a net zero balance in defined credits exchanged with the outside across the building's boundary within a specified period of time (typically one year). Depending on the target of the balance, the credits can be site energy, primary energy, CO₂ emissions, energy cost, etc., associated with the energy flow from or to the building. The energy flow is normally energy import and export from the building (or alternatively energy demand and generation when self-consumption is considered), but can also include imported fuel used in the building to generate energy, e.g. importing oil to produce heat by a boiler, gas to a micro-CHP to produce heat and electricity, etc. Various types of building loads can be encountered in the balance depending on the national codes and regulations or the project's definition, which may include appliances and plug load as well. This may also consider electric vehicle as a load inside the building's boundary depending on the definition. Publications produced by the above mentioned joint IEA SHC Task 40/EBC Annex 52 cover various details related to Net ZEB. In this concept, first it is to define a boundary of the building so that energy flow across it will be counted for the net energy balance. Depending on how it is defined, the physical boundary can be confined to the building's footprint or can otherwise extend to include the whole property, e.g. a detached parking lot where PV panels can be installed. In addition, investments in renewable energy installations that are not on the building site may be included in the balance if financed by the building's owner. Additionally, a building can purchase off-site renewable energy [7,8], which can make the balance explicitly based on covering the shortage by imported renewable energy. Depending on the agreement between different household owners in a community, mixed ownership of the renewable energy is possible, e.g. PV panels installed on other building's roof but is co-owned by more than one owner. Scognamiglio and Garde [9] discussed different options for PV panels' installation in a Net ZEB building, including onsite PV installation outside the footprint of the building or offsite detached or within another building footprint. Sartori et al. 2012 [8] indicated that the Net ZEB balance can be equal to or larger than zero, meaning that the Net ZEB can expand from zero to the positive side of the energy balance as a Positive Energy Building (PEB). The energy demand in the Net ZEB building is calculated according to the requirements for the indoor environment quality (IEQ). The indoor climate inside a Net ZEB building should be preserved at the required level and the indoor comfort is always taken as a first priority so that any compromise in the IEQ is not allowed [7,8]. Evaluation of the Net ZEB can be based on building performance simulations, where reference data are used for the weather, energy conversion factors, user behavior profiles [10], indoor air quality requirements, etc. Additionally, for real buildings, proper measurement and verification protocol [11] was set to check the compliance of the actual performance of a building with the Net ZEB requirements, where the energy import/export balance should be measured [8]. Moreover, there was extensive development in Load Matching and Grid Interaction (LMGI) indicators in the joint IEA SHC Task 40/EBC Annex 52 [12]. Related to this, and despite that the aim is to reach an annual energy balance in Net ZEB, the anal-

ysis can also include the energy matching between the building's generated energy and demand, as well as interactions with the energy networks, which is important to avoid stressing the grid if significant daily or seasonal mismatch between the availability of the renewable energy and energy demand exists. The role of the electrical and thermal energy storages in the building is vital in reducing the energy mismatching.

To reach Net Zero energy building levels and to reduce the emissions, the buildings has to use renewable energy sources and energy storage based on the local climatic conditions. For instance in the Mediterranean climate, Mazzeo et al. 2020 [13] studied and optimized PV-wind-battery system for the residential building. The study found that solar source is better in terms of environment and economics, while wind source can provide longer operating time. Better incentives for wind and battery can make such hybrid system economically feasible. In regard to Finland, the students' hostel in Kuopio (floor gross area 2120 m²) and the elderly house in Järvenpää (floor gross area 2550 m²) are examples of the first Net Zero Buildings in Finland. The Kuopio building was built in 2010 and the Järvenpää in 2011. The two buildings have advanced energy conservation measures in the envelope insulation, tightness, glazing, shading etc. that minimize the heating and cooling energy demands. However, electric energy for appliances and lighting constitutes a major part of the energy demand. PV and solar-thermal panels are the sources of energy generation in the Kuopio building, while integrated wind is also an option in the Järvenpää building. Other features of the buildings are: ground source ventilation preheating that increases the ventilation heat recovery efficiency to 80%, PV integrated shading on the south facing wall, and using high-energy class appliances, lighting and HVAC devices. Both buildings are connected to the district heating and the electricity grid. It is found that achieving the Net ZEB balance is a challenging task in the Finnish climate. For example, the available area for the PV and solar-thermal panels in the Kuopio building was insufficient to cover the demand. Therefore, the authors had to exclude the electric load for appliances and lighting in order to get to the net energy balance [14].

From the above, an important observation that can be made is the importance of providing enough top roof area to install PV and solar-thermal panels, in relation to the height in apartment buildings. This can be represented by the ratio of the roof area to the number of floors of the building. In the early design phase of the building, the shape of the building can be investigated to better manage the energy load. In this respect, Hasan et al. [15] used simulation-based optimization to minimize the heating energy and cooling energy demands of a cross-shaped office building by optimizing the number of floors and re-distributing the building's office rooms in four orientations while keeping the total floor area of the building constant.

From the regulations point of view, and according to the European Union's Energy Performance of Buildings Directive (EPBD 2010) [16], Nearly Zero Energy Building (NZEB) means a building that has a very high energy performance, where the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. The EPBD required all new buildings to be nearly zero energy buildings by the end of 2020. As noted for the Net ZEB, the required net annual energy balance can be difficult to achieve as it depends on the availability of sufficient renewable energy and the level of investments in onsite and offsite energy sources. On the other hand, the NZEB combines both the energetic and economic performance and does not specifically require reaching the net zero balance, but rather depends on the cost optimality method, which can approach and not necessarily reach the balance. In addition, it is a

general framework of NZEB evaluation with milestones that can be implemented by each EU member state.

A more ambitious level than Net ZEB and NZEB is the positive energy building (PEB) target, which is the focus in this article. Technically a PEB is a Net ZEB with an increased capacity of the renewable energy generation inside the boundary of the building in order to surpass the annual equality of the net energy balance. In this respect, the EU EXCESS project definition [17] and Alajuusela et al. 2021 [18] states “a positive energy building (PEB) is an energy efficient building that produces more energy than it uses via renewable sources, with high self-consumption rate and high energy flexibility, over a time span of one year. A high-quality indoor environment is an essential element in the PEB, maintaining the comfort and well-being of the building occupants. The PEB is also able to integrate the future technologies, such as electric vehicles with the motivation to maximize the onsite consumption and also share the surplus renewable energy”. As it can be noted, most of the elements of this definition are considered in the Net ZEB studies above. Additionally, other than exceeding the net annual energy balance, the other features indicated in the above definition “high self-consumption rate and high energy flexibility” are subjective since it is not specifying the required level of those.

On a larger scale of buildings, the definition of a Positive Energy District (PED) is under development. According to the Joint Programming Initiative-Urban Europe (JPI-UE) [19] “Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability”. In general, the focus of PED is on energy and emission reduction and sustainability, which can be effectively enabled in a smart city [20]. However, in the present study the scope is limited to the building level, rather than district level.

It is found in the recent study [21] that it is relatively easier to meet the PEB criterion by using technologies such as PV or PVT in Southern regions of Europe compared to the Nordics. This is due to the seasonal mismatch between the energy (heating) demand and availability of solar energy during the winters in the Nordics. Therefore, in the present scenario no PEB exist in the cold climatic conditions of Finland, as it is a challenge to reach the PEB level in the demanding environment [22]. The novelty in the current study lies in the technical design of apartment building’s energy system that aim to achieve the PEB level in Finland as an example of the Nordic climate by including or excluding various renewable energy technologies, such as heat pumps, PVT, deep boreholes seasonal storage, short term buffer storages and wind turbines, in the physical or extended virtual boundary of the building as well as considering or excluding some energy demands. Moreover, additional novelty comes from the proposed controls strategies to integrate these renewable energy technologies and energy storage, with PEB in the physical or extended boundary for the demo building, as these technologies are rarely used jointly on the buildings in real Finnish conditions. The purpose of the article is to provide the analysis for a demo site [23] that is planned to be constructed in Finland by 2023 as a PEB as no such site exists in Finland before. The article studies the energy efficiency of the building and different technologies that is planned to be used in the demo building with the aim to reach the PEB level, also learn about the limitations that can be faced and suggest proper solutions. The study on the PVT and deep boreholes integration with the building in the Nordic climate has not been carried out earlier. The aim is to study the emerging building technologies that can mitigate climate change

and exploit the use of renewable energy, building’s energy efficiency, energy storage and grid interaction at building scale. Parametric changes are made for close comparison of various technical and economical parameters and to evaluate the techno-economic perspective on the PEB level. Imported and exported electricity, life cycle cost (LCC) onsite energy fraction and matching factors are calculated for each scenario. Moreover physical and virtual boundaries of the building are proposed to address the challenges of reaching PEB in a cold climate.

The paper structure is as follows: a description about the method used in the article is defined in Section 2–5 that includes firstly the building design parameters, secondly the energy system design, components description and controls and finally the design variables for parametric study and costs data. The results, discussions and new ways to reach PEB level are mentioned in section 6, and finally the conclusion in section 7.

2. Methodology

To organize the methodology section, it is arranged in the following way. Section 3 discusses the building design and its parameters that are used in order to determine the energy demands for the demo building. Section 4 describes the renewable energy system design, controls and its technical parameters. Section 5 describes the energy system design variables that are used to perform the parametric analysis, the technical calculation and the costs data used in TRNSYS simulation software.

3. The building design

It is planned to construct an apartment building in the Kalasatama district [23] in Helsinki (60.19 N, 24.94 E) that has seven floors and includes 51 apartments with a total heated area of 4000 m². The total roof area is 400 m² and the building volume is 12800 m³.

3.1. The building design parameters

The building is an example of a new apartment building in Finland. It is designed to meet but also exceed the requirements of the national building regulations (Ministry of the Environment, Finland [24]) by reducing the energy demand and to make it a positive energy building. Since district heating highly contributes in the emissions in Finland [25], therefore, renewable energy generation can be instead used to cover the demand. Table 1 shows the design parameters of the simulated buildings in the study. The building’s load is consisted of heating and cooling demands (space heating and cooling, domestic hot water) and appliance and lighting loads.

The IDA-ICE software [26] is used to generate the building’s demand profiles, which is then integrated with the TRNSYS simulation model as an external text file.

Table 1
The design parameters of the demo building under study [23].

Parameters	Value
Floor area	4000 m ²
Walls (U value)	0.15 W/m ² K
Roof (U value)	0.09 W/m ² K
Floor (U value)	0.16 W/m ² K
Windows (U value)	0.6 W/m ² K
Heat recovery efficiency	75%
Ventilation air flow	0.5 dm ³ /sm ²

4. The energy system design

This section presents the details of the energy system components in section 4.1, the controls of the energy system in section 4.2 and the TRNSYS simulation model in section 4.3.

4.1. Energy system components

The proposed energy system is consisted of the following main components and as shown in Fig. 1:

- A roof mounted photovoltaic-thermal hybrid collector (PVT) (400 m²).
- A buffer tank charged by the PVT (with a volume of 20 m³ depending on the space available).
- A deep borehole thermal energy storage (BTES) (800 m deep) within the building boundary. It is charged via the buffer tank if excess energy is available in the tank.
- A central heat pump (HP) (60 kW), is used to charge a hot water storage tank by taking heat energy from the buffer tank or BTES during periods
- Domestic hot water (DHW) and space heating (SH) is provided by the hot water storage tank (2 m³).
- Another heat pump (HP) is used to provide cooling
- Cold water storage tank (2 m³) to the building. This is also used to charge the BTES by collecting the waste heat from the exhaust ventilation air of the building.

Realistic commercial component data of PVT [27], heat pumps [28], short term buffer (water) storage tanks [29,30], boreholes thermal energy storage [31,30] and wind turbines [32] from the companies are used, the way it is built for the real conditions. It is used in order to use the realistic performance and efficiency values of these components in the simulations.

4.2. Energy system operation

In this demo case there are two main systems, one is the buildings energy system for the whole building serving all apartments and the second one is the energy system inside each apartments. As both of these systems are interconnected, there is a controller that can aim to maximize the performance of the energy system. The main layout and components of the energy systems are shown in Fig. 1. The control scheme of the energy system is designed so that the PVT is cooled down by providing cold water from the buffer tank in order to maximize the electrical and thermal production from the PVT. When the buffer tank is charged at a certain level, the excess heat energy is dumped in the BTES. The HP takes the energy from the buffer tank or from the BTES to provide space heating and domestic hot water to the building at higher temperature. Cooling is provided to the building using the HP, cold tank and ventilation unit. The PVT is used to charge the buffer tank mainly if the buffer tank temperature is lower than 55 °C, where it is heated to 60 °C. The PVT pump is used when the solar radiation is above 700 kJ/hr.m² and the PVT flow is recirculated so that the buffer tank inlet temperature is higher than 20 °C to avoid cooling of the tank and to heat the working fluid (glycol mixture of 40%) before sending it to the buffer tank. The hot tank is used to provide the space heating (SH) and domestic hot water (DHW) to the building. If the hot tank temperature is lower than 60 °C, it is heated to 65 °C by the heat pump. The heat pump takes energy from the buffer tank or BTES at maximum 25 °C due to the technical limitations. If the buffer tank temperature drops below 15 °C during the period when solar energy is not available, the heat pump takes energy from the BTES directly. Any excess energy present in the buffer tank is transferred to the BTES when the buffer tank temperature is higher than 35 °C until the buffer tank temperature drops to 30 °C. The working fluid here considered is a glycol mixture of 20%. Space heating is provided by passing the water through a heat exchanger that is connected to the hot tank. The space heating to the building is provided at a temperature that varies between 20 °C and 45 °C, depending on the outdoor temperature. It is

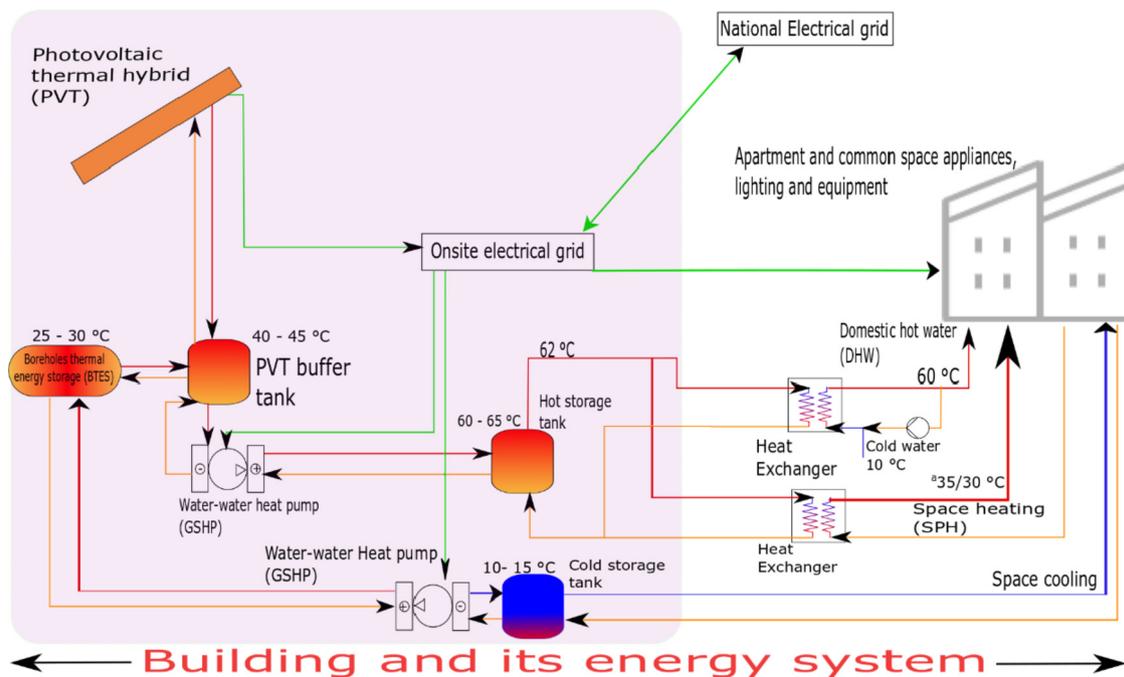


Fig. 1. The energy system layout.

slightly higher than the designed temperature in order to include the losses. The domestic hot water (DHW) is provided by passing the incoming cold city water through the hot tank via a heat exchanger [33]. The water is heated up to 58 °C before being supplied to the tap and this water is recirculated, within the system to keep the DHW warm for the consumers. There is also backup heating provided by a direct electric heater in case the system is not able to supply the water at the above mentioned temperature. The space cooling is provided by the separate cooling tank, in a way that the space cooling tank temperature is kept at 10 °C; if the tank temperature increases to 16 °C the heat pump is used to cool the tank. The heat from the building is exchanged with the cooling tank to provide cooling to the building during summer. The heat collected from the building ventilation exhaust air is used to charge the BTES through the heat pump to recirculate the waste heat in the system. The extended boundary and the renewable energy generation in the extended virtual boundary is also considered for PEBs, which is further discussed in section 6.3.

4.3. Simulation of the energy system

The dynamic simulation software (TRNSYS) [34] is used for the simulations of the proposed energy system described above. This simulation software has been used and validated by Drake Landing Community, Canada for similar applications [35]. The main input files to the energy system simulation model are the building's heating and cooling demand profiles produced by the IDA-ICE software and the weather data. In the future the climate change may impact the indoor comforts in the buildings depending on the geographical locations [36,37]. However for the ease of calculations and construction practice used in Finland the simulations were carried out using test reference year [34] weather file for Helsinki, which is the weather data used in the national building performance regulations and the energy label calculations.

5. Parametric analysis

To provide the behavior and complete analysis of the system under various condition, the performance of the system is evaluated by varying the design variables of the energy system. The imported, exported electricity and energy matching are calculated for each scenario to estimate the technical performance. In addition, the economic (life cycle cost) of the energy system is also calculated. The aim is to demonstrate the techno-economic performance of PEBs and its feasibility. The components that are used in the parametric study of the energy system simulations are shown in the following section 5.1. The technical calculations and the economic values used to calculate the life cycle costs are shown in the section 5.2 and 5.3, respectively.

5.1. Energy system design variables

The design variables are shown in Table 2, which are selected to show the behavior of the energy system and possible ways to meet the PEB level. These generation and storage components can impact the performance of the system [38,39]. The investment cost

Table 2
The variables used for the parametric study in the TRNSYS.

Component	Parametric values
Photovoltaic-thermal collector (m ²)	100, 200, 300, 400
PVT Buffer tank (m ³)	10, 20, 30, 40, 50
Deep borehole height ratio	1, 3, 5
Deep borehole density (BH(s)/m ² BH area)	0.05, 0.10, 0.15

for the building and the main components of the system are discussed in section 5.3. The main results of the building and energy system simulations are discussed in section 6.

5.2. Energy calculation

The heat and electricity energy flow are balanced for every time step of 1 h. All heating demand has to be met by the local system by either the onsite produced energy or by imported energy. However, excess electricity generated via the PVT is exported to the grid. Any shortfall is balanced by imported electricity from the grid [40]. The mathematical expression for the energy balance at each time step of the simulation is shown in equation (1):

$$E = GN + ST - (A + B) \tag{1}$$

Where E is the imported electricity when it is negative and exported electricity when it is positive, GN is the electricity generated by the renewable energy sources, ST is the stored energy, A is the energy consumed by all the heat pumps, back up electric heating and auxiliaries of the heating and cooling and B is the electricity demand of the building and property lighting and appliances.

5.2.1. Energy matching analysis

The on-site energy fraction (OEF) and onsite energy fraction (OEM) of electricity [41] are also calculated to analyze the matching factors and onsite consumption of the renewable energy generation. OEF calculates the amount of the demand that is met by the onsite produced electricity. OEM calculates the amount of the locally generated electricity that is used onsite to meet the building demand [41].

5.3. Life cycle cost calculation

For cost estimation, the simple life cycle cost (LCC) is considered that includes the investment cost of the energy system and the energy operational cost. The building cost is also included to estimate the cost ratio of the energy system and the LCC. The assumed average cost of the main components are given in the Table 3. The average import electricity price is 80 €/MWh and the export electricity price is 35 €/MWh [42], including the distribution cost and taxes. The interest rate is assumed as 3% and 25 years are considered for the operational life of the system [22]. The maintenance and disposal costs are not included in the study, a similar approach was carried out in the earlier study [43].

6. Results and discussion

The results and discussion section is arranged in the following way. Section 6.1 shows the building demand profiles for heating,

Table 3
Design variables and components average investment costs.

Design variables	Investment Cost	Reference
Photovoltaic-thermal panels (m ²)	323 €/m ²	[44]
Wind turbine (kW)	3000 €/kW	[45]
Tank (m ³)	800 €/m ³	[30]
Water-water heat pump (kW _{thermal})	325 €/kW	[46]
BTES aspect ratio	33.5€/m(drilling) + 3€/m ³ (excavation for insulation) + 88€/m ³ (1.5 m insulation thickness)	[46]
BTES volume (m ³)		
Building	4000 €/m ²	[47]

cooling and plug loads. Section 6.2 shows the techno-economic performance of the energy system integrated with the building based on PVT sizing, buffer tanks sizing and deep boreholes design. Section 6.3 shows the techno-economic performance of the energy system integrated with the building when the physical boundary is extended virtually and geometry of the building is changed or wind turbines are installed in order to reach PEB level.

6.1. Heating, cooling and plug loads

The heating system is a low temperature for the floor heating and the ventilation heating coil (35 °C at design conditions). The load profile for the heating of the studied apartment building is shown in Fig. 2 based on the hourly simulation results. The heating demand includes the space heating and the ventilation air heating. It is observed in Fig. 2 that the maximum space heating load occurs during the months of January, February and December. The monthly cooling load of the supply air of the air-handling unit (AHU) is presented in Fig. 2. According to the simulations, a small space cooling system is required in summer. The passive cooling design of the windows, which has g-value = 0.38 (transmittance value), reduces the cooling load. However, to meet the small cooling load to prevent the indoor air temperature to exceed 27 °C, which is the critical limit for the cooling in the Finnish regulations [24] cooling energy is supplied through the cold tank. The excess heat that is removed from the building is also utilized to regenerate the boreholes as mentioned in section 4.1. It is observed in Fig. 2 that higher space cooling demand occurs during the months of June, July and August. The heating and cooling load profiles (Fig. 2) are used as input to the energy system model.

According to these results, the heating load is 15.4 kWh/m²/yr, which is low due to the better insulation and windows. The domestic hot water load is 42.1 kWh/m²/yr, which is high due to its high supply temperature (around 60 °C) and the recirculation losses. The user profile is considered in calculating the DHW energy demand [48]. The cooling load for the building is 2.36 kWh/m²/yr, which is quite low as in general summer is short and the average summer temperature is around 15–20 °C in Finland [49]. The load for lighting and appliances of the building is 36.9 kWh/m²/yr, where around 73 % of it is used for appliances and the remaining 27% for the lighting. Here onwards the lighting and appliances load together are referred as plug load to simplify the term.

6.2. Energy system performance analysis

This section presents and compares the technical and economic performance of the energy system that is integrated within the physical boundary of the demo building in order to meet the PEB criterion. The import and export of electricity, OEF and OEM and LCC are calculated that varies due to the variations in parameters and design variables.

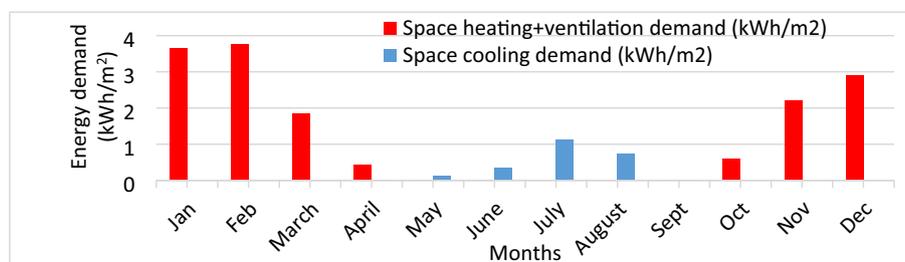


Fig. 2. Energy system demand during one year, red bars: monthly heating, blue bars: monthly cooling demand. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6.2.1. PVT sizing

6.2.1.1. *The case including the plug loads.* The energy performance of the energy system is shown in the Fig. 3 with respect to the various PVT sizing, when all loads, i.e. heating, cooling and plug loads (lighting and appliances), are considered in estimating the PEB level of the building. As expected, it can be observed in Fig. 3 that when the PVT area starts to increase the electricity import starts to decrease and vice versa. Overall, when the PVT area increases from 100 m² to 400 m², the electricity import decreases from 160 MWh to 139 MWh and the electricity export increases from 0 to 16 MWh. Fig. 3 shows that even though the PVT area reaches 400 m², the building is still not able to meet the PEB level, i.e. the electricity import is still significantly higher than the electricity export, which is even very far from reaching the Net ZEB level. This shows that when all the demands of the building (heating, cooling and the plug loads) are included, it is not possible for the apartment building to reach the PEB level in the studied case. More PVT cannot be installed due to the limited roof and also not in close vicinity to the footprint of the building due to the highly dense urban area.

Fig. 4 shows the cost breakdown of the life cycle cost of the investment cost of the different energy system components and the operating energy cost when including the plug loads for different PVT areas as well as the building cost. Each single configuration on the x-axis of Fig. 4 corresponds to the same solution shown in Fig. 3. Generally, the solutions on the left side are low performing and, therefore, the cost is lower while on the right side, they are high performing with higher cost. The investment cost of the energy system is around 47–62% of the LCC. The ratio of the energy system investment cost to the building investment cost is around 1.2–1.9%. This shows that the building cost is significantly much higher compared to the energy system cost. When the PVT area is 100 m², the largest investment cost is in the boreholes. As the PVT area increases to 400 m², the largest investment is in the PVT. The costs of the tanks and heat pump are rather small portion of the LCC. It is also observed that the energy cost is around 56 €/m² when the PVT area is 100 m², and it is 46 €/m² when the PVT area is 400 m². This shows that as the PVT area increases, the energy cost reduces. However due to the high energy demand, the energy cost is still significantly large.

In the case when including the plug loads, the onsite energy fraction (OEF) reaches around 63% with 400 m² PVT area. This means that 63% of the total demand of the building is covered by the onsite generation onsite and the rest is covered by the imported electricity. In this case the onsite energy matching (OEM) is around 66%, which means that 66% of the onsite generation is used onsite and the rest is exported.

6.2.1.2. *The case excluding the plug loads.* As indicated in the introduction, the two apartment buildings that were constructed in Finland in 2010 and 2011 were designed to be Net ZEB when the electric loads for the appliances and lighting were excluded in

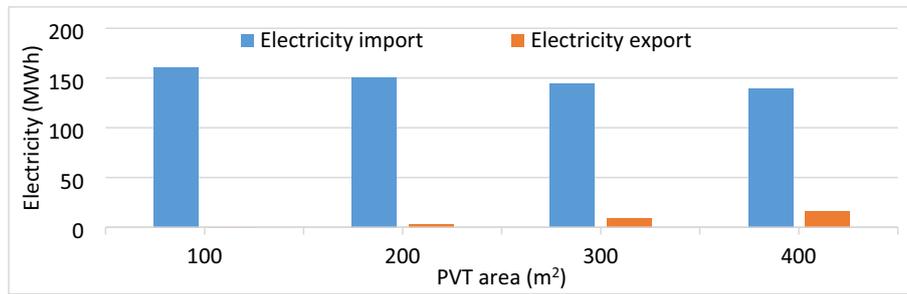


Fig. 3. The import and export of electricity for different PVT areas-case when including the plug loads.

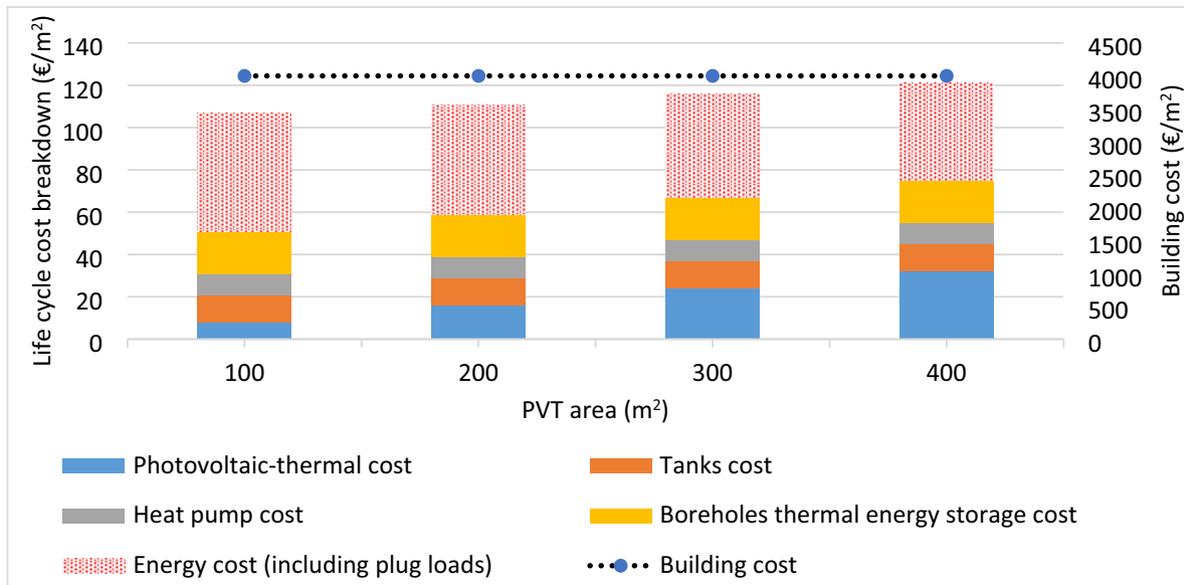


Fig. 4. The life cycle cost breakdown and the building cost for different PVT areas-case when including the plug loads.

the energy balance. Similarly, the apartment building under consideration is also studied without the appliances and lighting loads (i.e. plug loads). The energy performance of the building and its energy system in terms of electricity import and export is shown in Fig. 5 with various PVT areas, when excluding the plug loads. Overall, the electricity import decreases from 22.6 MWh to 16 MWh and the electricity export increases from 8.8 MWh to 40 MWh when the PVT area increases from 100 m² to 400 m². Fig. 5 shows that when the PVT area is higher than 200 m² the building is able to meet the PEB criterion, i.e. the electricity export starts to be higher than the electricity import. Therefore, it appears that with the existing limitation in the availability of roof area, the solution to reach the PEB level is to include only the heating and cool-

ing demand in the energy balance and exclude the electricity demand of the plug loads. However, this is not in accordance with the Finnish building code, which takes all types of energy in account.

In Fig. 6, the investment cost on the energy system is around 88–100% of the LCC for the case excluding the plug loads. It is also observed that the energy cost is around 6.5 €/m² when the PVT area is 100 m². On the other hand, the energy cost is -0.3 €/m² when the PVT area is 400 m². This shows that as the PVT area increases, the building or the energy system owners will not only reduce the electricity import annually but they can have positive cash flow by selling excess renewable energy to the grid. When comparing Fig. 5 and Fig. 6 it is observed that even though the

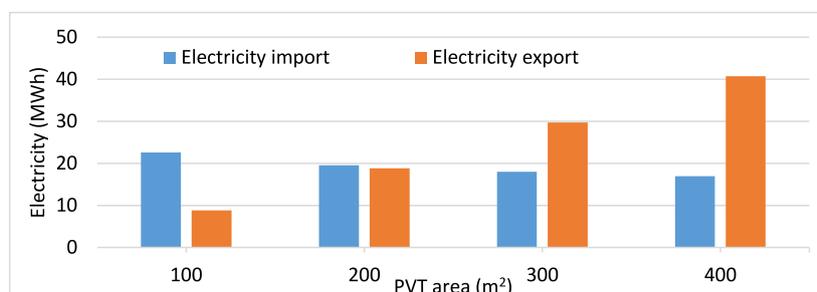


Fig. 5. The import and export of electricity for different PVT areas-case when excluding the plug loads.

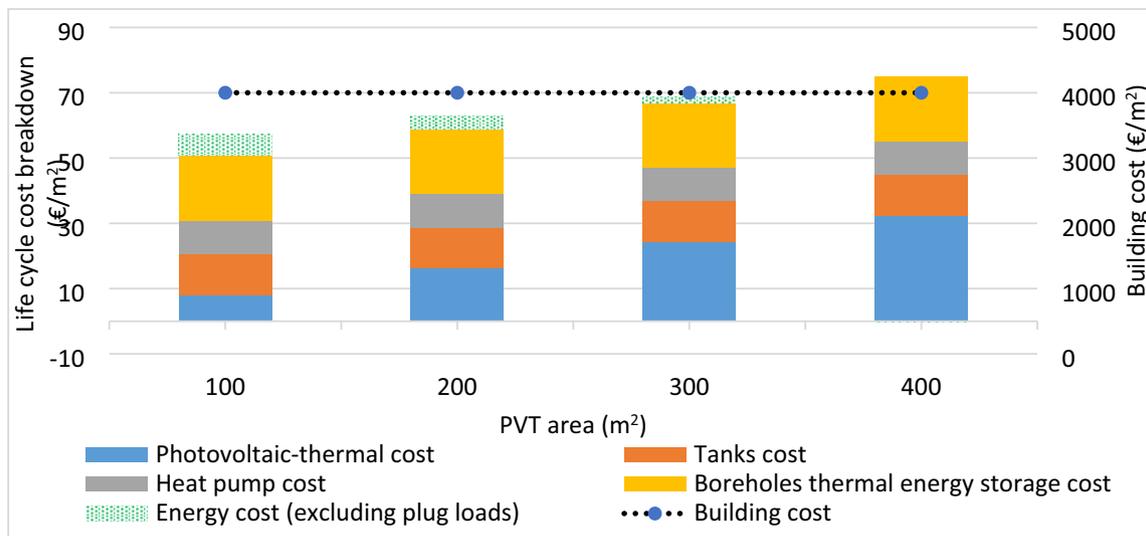


Fig. 6. The life cycle cost breakdown and the building cost for different PVT areas-case when excluding the plug loads.

building is able to reach PEB level when the PVT area is slightly higher than 200 m², the operational energy cost is still around 3.92 €/m², rather than negative cost. This is due to higher cost of the imported electricity compared to the exported electricity.

In the case excluding the plug loads the onsite energy fraction (OEF) reaches around 95% when the PVT area is 400 m². In this case the onsite energy matching (OEM) is around 16%, which means that most of the produced electricity is exported.

6.2.2. PVT buffer tank size-case excluding the plug loads

The electricity import and export is shown in Fig. 7 with various PVT buffer tank sizes when excluding the plug loads. The PVT area is assumed to be 400 m² in this calculation. Overall, the electricity import decreases from 18.4 MWh to 16 MWh and the electricity export increases from 40 MWh to 42 MWh when the PVT buffer tank volume increases from 10 m³ to 50 m³. This shows better performance of the energy system due to the large amount of instant cold water available in the storage tank to extract heat from the PVT. Fig. 7 shows that when the volume of the tank increases, the heat generation by the PVT increases from 69 MWh to 84 MWh, resulting in decrease in import and increase in export of the electricity. However, the buffer storage tank needs space for installation, which is a critical point to be considered in buildings that are constructed in densely populated urban areas.

In Fig. 8, it is shown that the investment cost in the energy system is around 99–100% of the LCC. Compared to the building cost,

the ratio of the energy system cost is around 1.7–1.87%. The energy cost is 0.23 €/m² when the tank volume is 10 m³ and is -0.50 €/m² when the tank volume is 50 m³. This shows that, as the volume of the tank increases, the building or the energy system owners will not only reduce the electricity import annually, but they can have positive cash flow by selling excess emission free energy to the grid.

Boreholes thermal energy storage (BTES) design – Case excluding the plug loads

To estimate the effect of the BTES design on the overall performance of the energy system, a parametric study is carried out based on the boreholes height ratio and boreholes density indicated in Table 2. Borehole height ratio refers to the height to the width ratio of the boreholes field. The energy performance of the building and its energy system in terms of electricity import and export is shown in Fig. 9 with various BTES height ratio. It is assumed that the PVT area is 400 m² in this case, the volume of the boreholes is 1000 m³ and boreholes density is 0.15 boreholes/m³ when excluding the plug loads. Boreholes density refers to the number of boreholes per cross section area of the boreholes field. Overall, the electricity import decreases from 46.8 MWh to 18.5 MWh and the electricity export increases from 27 MWh to 39 MWh when the BTES height ratio increases from 1 to 5. It is observed that when the ratio is 1, the building may not reach the PEB level. This is due to less storage capacity that is available to store heat energy during summer. As a result the heat pump source

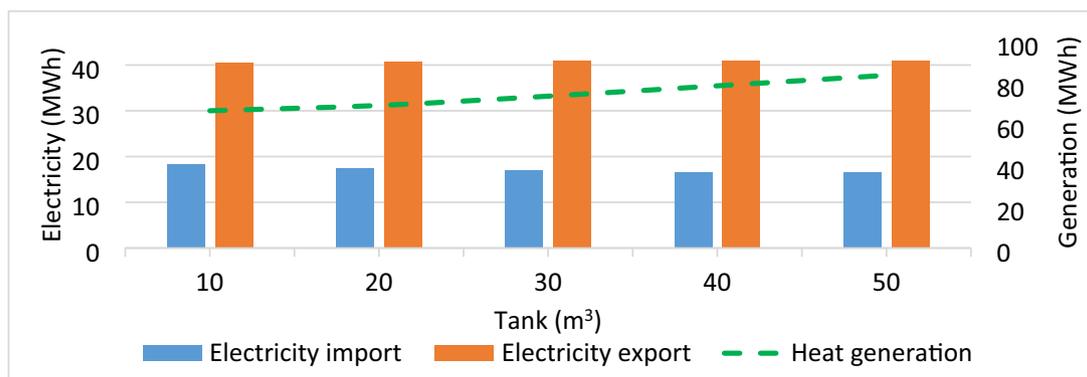


Fig. 7. The import and export of electricity for different PVT's buffer tank size (with 400 m² PVT area) – case when excluding the plug loads.

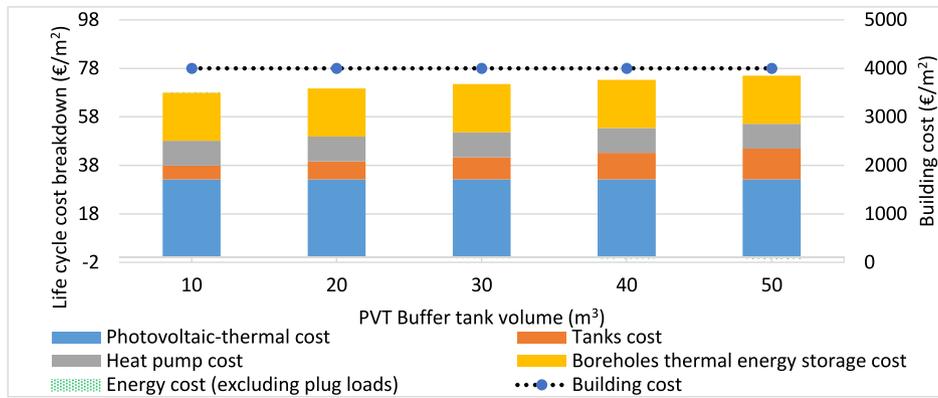


Fig. 8. The life cycle cost breakdown and the building cost for different PVT buffer tank capacity-case when excluding the plug loads.

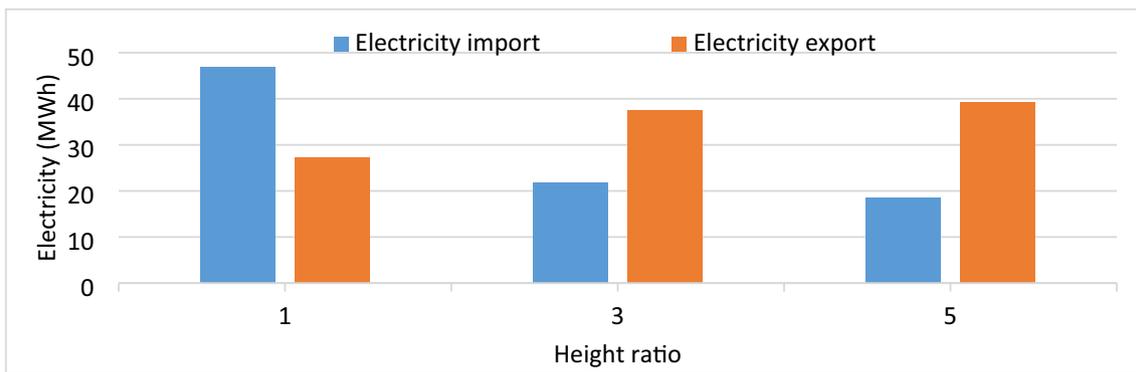


Fig. 9. The import and export of electricity for different BTES height ratio-case when excluding the plug loads.

side has less energy available from BTES during winters causing low COP and higher import of electricity to meet the heating demand. On the other hand, when the boreholes ratio increases to 3 and 5 the building is able to reach PEB level. With larger height, the boreholes have larger storage capacity available that can be charged during summer and discharged during winter. Longer height is therefore better for the buildings to reach the PEB level in the studied climate conditions.

In Fig. 10 the investment cost on the energy system is around 93–98% of the LCC. Compared to the building cost, the ratio of the energy system cost is around 1.4–1.51%. It is observed that

when the height ratio of the boreholes increases, the cost of the boreholes reduces. The boreholes cost reduces from 5.5 €/m² when the height ratio is 1 to 2.7 €/m² when the height ratio increases to 5. This is because as the height ratio increases, the number of boreholes reduced and the cross section area of the storage also decreases, resulting in lower excavation and drilling cost of the boreholes. The energy cost also reduced from 12.1 €/m² when the height ratio is 1 to 0.46 €/m² when the height ratio is 5. This shows that the boreholes height ratio can impact the energy cost and the LCC of the energy system. As the boreholes height ratio

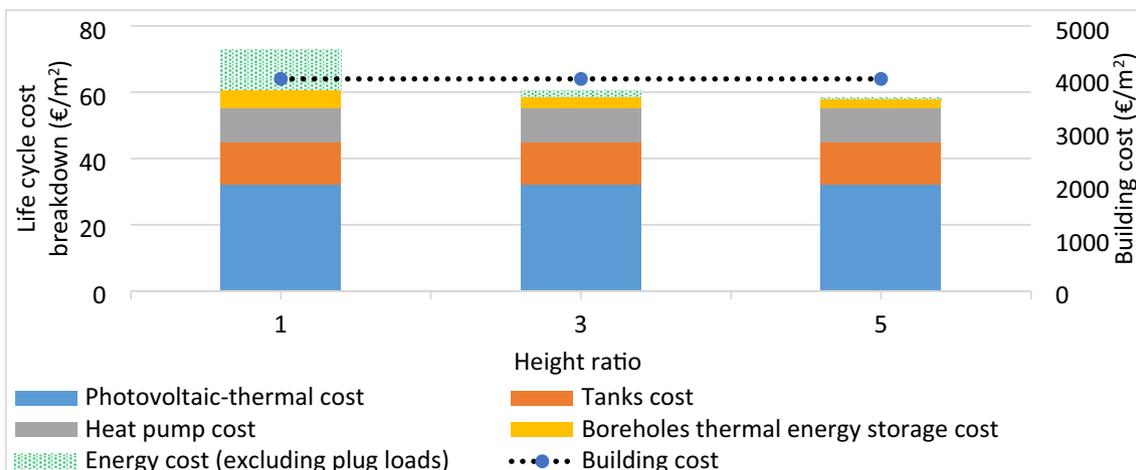


Fig. 10. The life cycle cost breakdown and the building cost for different BTES height ratio-case when excluding the plug loads.

increases the LCC reduces along with the investment cost on the boreholes.

The energy performance of the building and its energy system is shown in Fig. 11 with various boreholes density. It is assumed that the PVT area is 400 m² for all the cases and the volume of the boreholes is 1000 m³ when excluding the plug loads. The numbers of boreholes are 2, 3 and 5 for the 0.05, 0.1 and 0.15 boreholes density respectively. Overall, the electricity import increases from 16 MWh to 18.5 MWh and the electricity export decreases from 41 MWh to 39 MWh when the boreholes density increases from 0.05 to 0.15, i.e. higher number of boreholes per m² cross section area. It is observed that the import of electricity increases when the boreholes density increases. This is because due to the higher boreholes density, the ground cools down quickly when energy is taken out from a smaller area.

In Fig. 12 the investment cost on the energy system is around 99–100% of the LCC. Compared to the building cost, the ratio of the energy system cost is around 1.4%. It is observed that when the boreholes density of the boreholes increases the cost of the boreholes increases. The boreholes cost increased from 1.9 €/m² when the boreholes density is 0.05 to 2.7 €/m² when the boreholes density increased to 0.15. This is because as the boreholes ratio increases, the number of boreholes increased, resulting in higher drilling cost of the boreholes. The energy cost also increased from –0.6 €/m² when the boreholes density is 0.05, to 0.46 €/m² when the density is 0.15. This shows that the boreholes density can impact the energy cost and the LCC of the energy system. One important observation made is that the borehole efficiency is low, in the range of 30–50 % depending on the boreholes geometry. Therefore, instead of storing heat via the boreholes in the ground, it will more efficient to export heat to a neighboring building when the temperature level of the PVT is high enough, that can make better use of the excess heat and could improve the energy performance of the building.

Reaching PEB

It is found in the above section 6.2 that reaching PEB criterion is a challenge in the Nordic climatic conditions, if the all the demands (such as heating, cooling and plug loads) are included in the energy balance calculations and renewable energy components are integrated within the physical boundary of the building. Therefore, there can be different types of PEBs according to the boundary of the building similar to that proposed by the European Energy Research Alliance (EERA) for Positive Energy Districts (PED) [50] and as discussed in the study by Lindholm et al. [51]. It can be assumed that the boundary of the demo building can extend outside its physical limits to a virtual boundary, where it includes all the components of the energy system that are invested in. The conceptual picture of the PEB with virtual and extended boundary is shown in Fig. 13. The renewable energy sources, storage and any other loads such as electric vehicles, can be located outside the physical building boundary as shown in Fig. 13. To reach the PEB level, the onsite renewable energy and the virtual

generation sources present in the extended boundary of the building should together have higher combined supply than the energy demand of the building.

Table 4 shows the parameters used to study the performance of the demo building when considering the virtual boundary with variable design parameters of the energy system. Two components considered in the virtual boundary are the shape of the building (varying the height and roof area) and the wind turbines as shown in Table 4. These variables are selected to provide a wide range of possible solutions to meet the PEB level. The investment cost for the LCC calculations of the design variables are shown in Table 4. In this section the calculations are carried out when all the loads of the building are included.

6.2.3. The building's geometry variation – case including the plug loads

The energy performance of the building is shown in Fig. 14 with respect to various building volume to height ratios when all loads, i.e. heating, cooling and plug loads, are considered to estimate the PEB level of the building. It is assumed that the height of the building is reduced from 32 m to 24 m, 16 m and 8 m and instead the building's footprint is increased while keeping the total floor area of the building constant. These correspond to a roof area of 400 m², 530 m², 800 m² and 1600 m², respectively. It is assumed that whole roof area is covered by the PVT. Larger roof (or PVT) areas are selected because as was shown in Fig. 3, the demo building cannot reach the PEB level even though all the roof was covered by PVT when including the plug loads. Therefore the building's height is decreased to increase the available roof area. It can be observed in Fig. 14 that when the roof (PVT) area increases, the electricity import decreases and vice versa. When the PVT area reaches 1600 m², the building is able to reach the PEB level as the electricity import (118 MWh) is lower than the electricity export (130 MWh). In order to reach the PEB criterion, it is important to design the building with larger roof area. However, this could be a big challenge in a dense urban areas due to the expensive land space. Another option is to identify additional space outside the building in a nearby lot to install more PVT, which could be expensive as well.

Fig. 15 shows that the investment cost of the energy system is around 62–88% of the LCC. The ratio of the energy system cost to the building cost is around 1.9–4.2%. This shows that compared to the cost ratios in section 6.2 the energy system cost is slightly higher, this is due to large PVT capacities considered in this scenario. When the PVT area is around 400 m² the largest cost is the energy cost i.e. around 46.3 €/m². As the PVT area increases to 1600 m², the largest investment is in the PVT and as a result the energy cost reduced to 21 €/m². This shows that as the PVT area increases, the energy cost reduces, however the investment cost increases in such a case due to the larger PVT area.

Fig. 16 shows the onsite energy fraction (OEF) and the onsite energy matching (OEM) of the electricity of the PEB and its energy system. It can be observed in Fig. 16 that as the PVT area increases

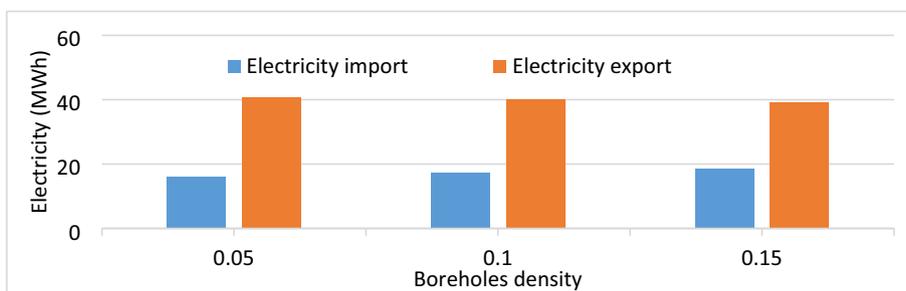


Fig. 11. The import and export of electricity for different BTES density – case when excluding the plug loads.

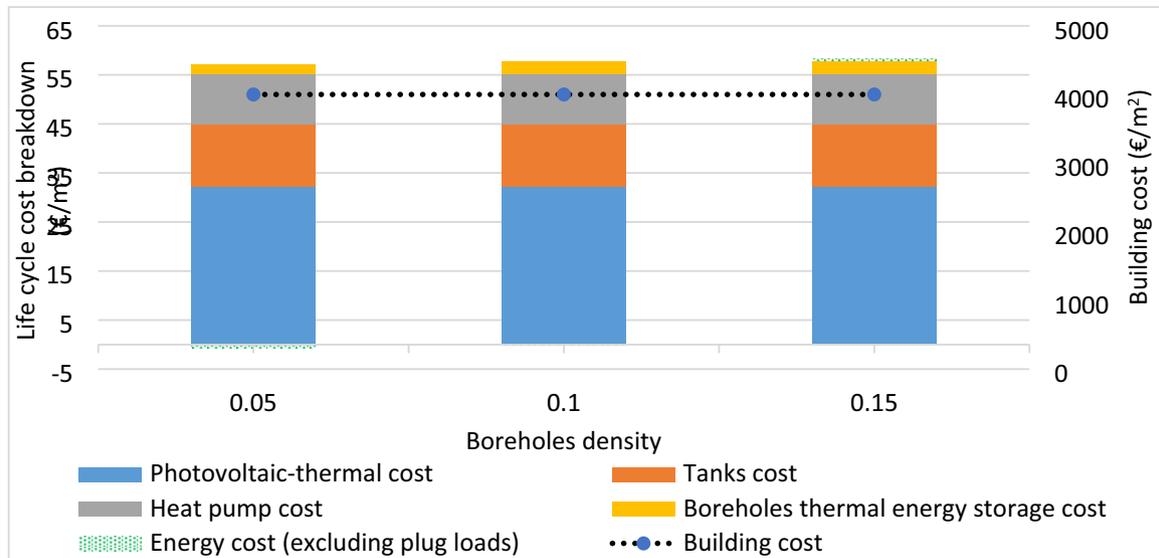


Fig. 12. The life cycle cost breakdown and the building cost for different BTES density-case when excluding plug loads.

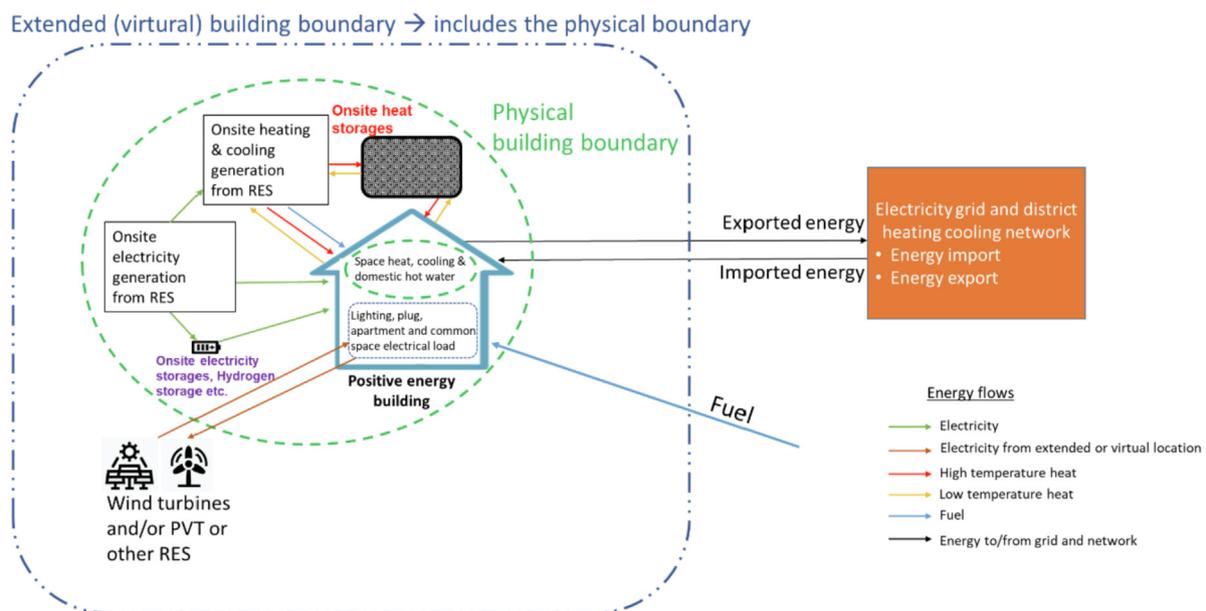


Fig. 13. The positive energy building concept with the extended boundary that includes the physical and extended (virtual) building boundary.

Table 4

The variables used for the parametric study for the virtual boundary condition for the building to reach PEB level.

Component	Parametric values	Investment cost	Reference
Roof area	corresponding PVT area: 400, 530, 800, 1600	PVT 323 €/m ²	[44]
Wind turbine power (kW)	0, 30, 45, 60, 75	3000 €/kW	[45]

due to the increase in the roof area in to the virtual boundary, the OEF increases. This shows that with large PVT area the OEF reaches around 70%, which means that 70% of the total demand of the building is covered by the generation done onsite and in the virtual boundary, while the rest is covered by the imported electricity. Similarly Fig. 16 shows that the onsite energy matching (OEM)

decreases as the size of the PVT increases. The OEM varies between 66% and 31% depending on the PVT area. When the PVT area is large the OEM is around 31%. This means that when the PVT area is large, it produces larger amount of energy, however only 31% is used onsite by the building before being exported. When comparing the OEM and OEF it can be understood that when the PVT area is large, the OEF is large around 70%, on the other hand the OEM is 31%. This means that when the PVT area is large, the onsite utilization of the generated electricity is 31%, however 70% of the onsite building demand is met by the large PVT area. This is opposite when the PVT area is small, the OEF decreases, while the OEM increases as the PVT.

6.2.4. Wind turbines – case including the plug loads

Wind turbines are important energy generation components. It is used to generate electricity locally to the system and to reduce the grid dependency. TRNSYS Type 90 is used to model the wind

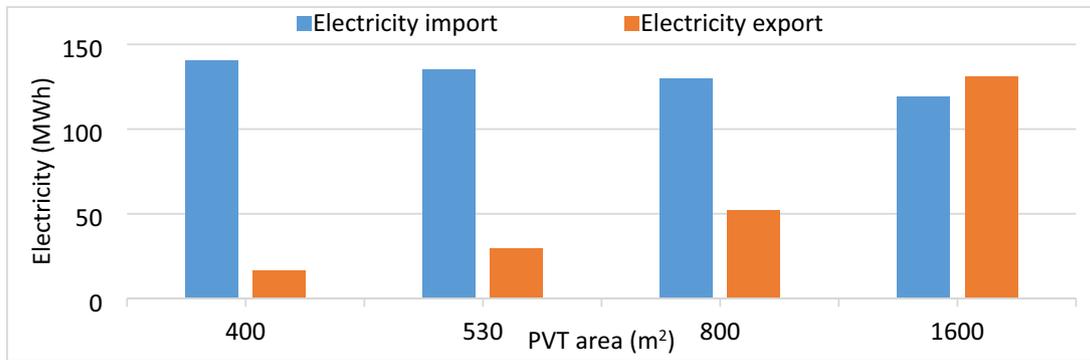


Fig. 14. The import and export of electricity for different building shape and larger PVT capacity-case when including the plug loads.

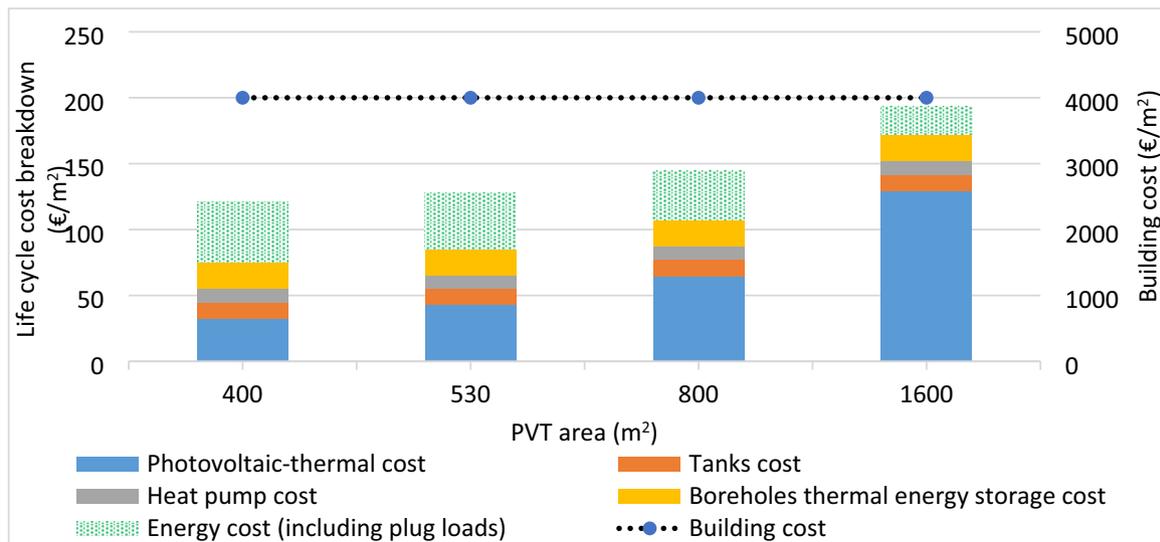


Fig. 15. The life cycle cost breakdown vs the building cost for different building shape and larger PVT capacity-case when including the plug loads.

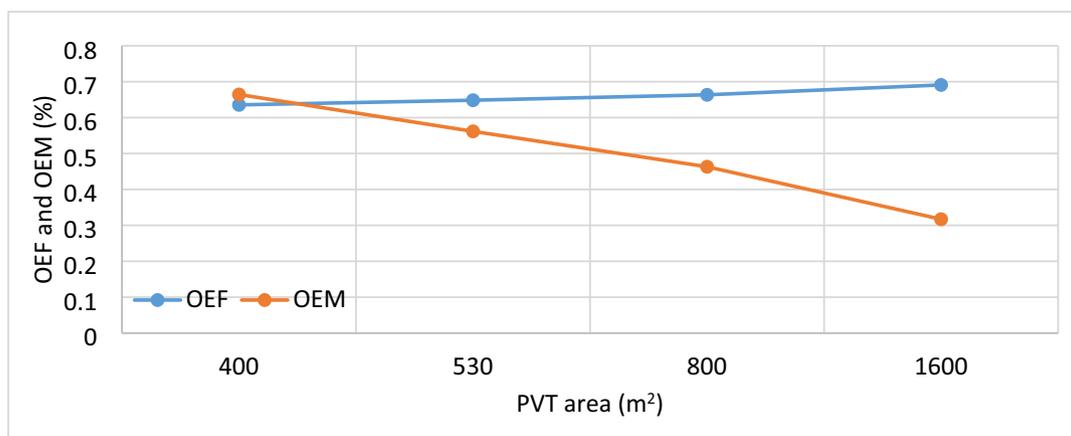


Fig. 16. The onsite energy fraction and matching for different building shape and larger PVT capacity-case when including the plug loads.

turbines. The turbines performance with respect to the wind velocity is from the commercial data [32]. The number of wind turbines power are assumed to be variable as shown in Table 4. In this case, the building roof area is fixed and is covered by PVT (400 m²), and no excess space is available to install any other energy source such as wind turbine, therefore the boundary is extended outside the building lot in the virtual boundary away from the building. The

energy performance of the building is shown in Fig. 17 with various wind turbine power when all loads, i.e. heating, cooling and plug loads, are considered. This is done to find the minimum wind turbine power needed to reach the PEB level along with the (400 m²) PVT area. Obviously when the wind turbine capacity increases, the electricity import decreases and the export increases. It is observed in Fig. 17 that when there is only the

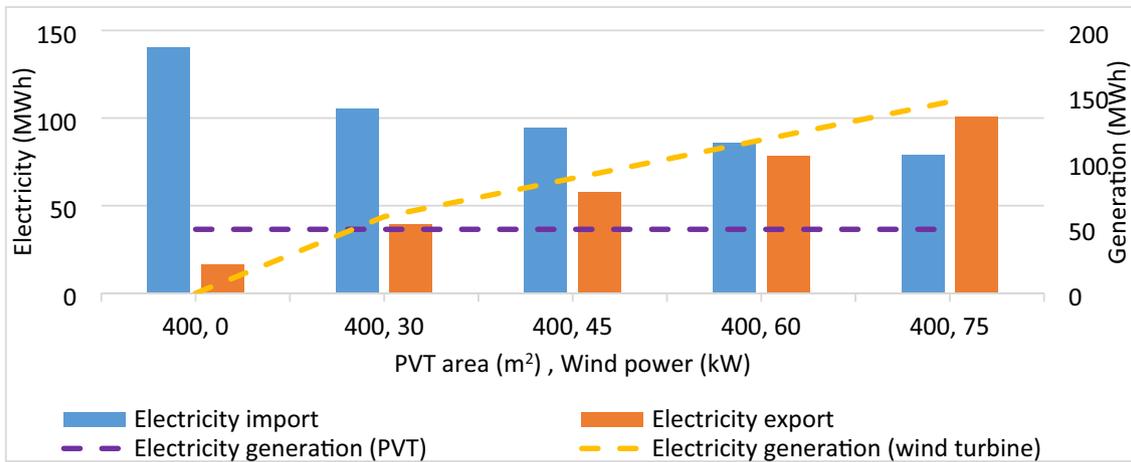


Fig. 17. The import and export of electricity for 400 m² PVT and different wind turbine capacities-case when including the plug loads.

PVT (400 m²), the building is not able to reach the PEB level, but when a wind power of 75 kW is added, the building is able to reach the PEB level. In this case, the electricity import is around 79 MWh and the electricity export is 100 MWh, which is due to the increase in the electricity generation from the wind turbine (yellow dotted line) as shown in the Fig. 17. Therefore, it is important to identify the available land space outside the building boundary in a virtual boundary where all the smaller units of wind turbines can be installed or a single large wind turbine is enough. With smaller capacities of multiple wind turbines, the reliability of the system would improve, while with a single large turbine, the reliability issue can arise.

Fig. 18 shows that the investment cost of the energy system consisted of the PVT and wind turbine is around 62–91% of the LCC. The ratio of the energy system cost to the building cost is around 1.9–3.2%. This shows that compared to the cost ratios in section 6.2, the energy system cost is slightly higher. When the wind turbine capacity is 0, the largest cost is the energy cost 46.3 €/m². As the wind turbine capacity increases to 75 kW, the largest investment is in the wind turbines and as a result, the energy cost is reduced to 12 €/m². Comparing the increase in the wind turbine capacity (in Fig. 18) to the addition of the PVT area in the virtual boundary (in Fig. 15), the LCC of the wind turbine scenario is

26% lower. This is because the electricity production of the wind turbine is higher compared to the PVT as shown in Fig. 17.

The wind turbine offers higher matching with the demand around the year, meaning that it reduces the amount of electricity import, which is at higher price per kW than export price. While the PVT generation is focused in summer when the demand is low and the surplus is exported at a reduced price to the grid. Fig. 19 shows the onsite energy fraction (OEF) and the onsite energy matching (OEM) of the electricity. It can be observed that as the wind turbine capacity increases, the OEF increases and the OEM decreases. The OEF and OEM is higher in the case where the wind turbines are used in the virtual boundary (in Fig. 19), compared to the case where the PVT area is increased in the virtual boundary (in Fig. 16). With largest wind turbine (75 kW), the OEF reaches around 80%, which means that 80% of the total demand of the building is covered by its own generation, while the rest is covered by the imported electricity. In this case the OEM is around 48%, this means that 48% of the generation is used onsite by the building and the rest is exported.

7. Conclusions

This article discusses and analyze various technologies (such as PVT, wind turbines, seasonal and short term buffer heat storage,

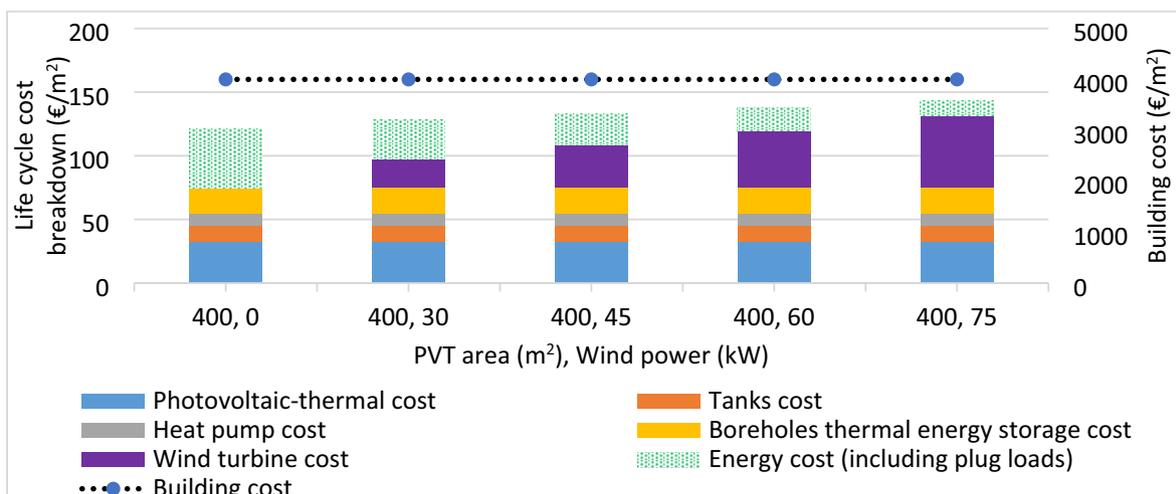


Fig. 18. The life cycle cost breakdown and the building cost for 400 m² PVT and different wind turbine capacities-case when including the plug loads.

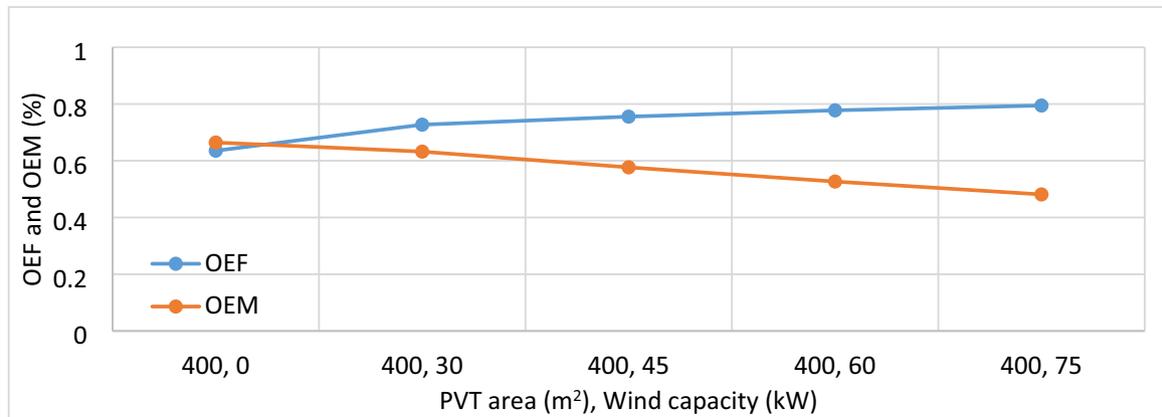


Fig. 19. The onsite energy fraction and matching for 400 m² PVT and different wind turbine capacities—case when including the plug loads.

heat pumps, district heating/cooling etc.), their integration with the building, its controls strategies, types of load included in the energy balance and definition of building boundaries across which the balance is calculated, with the aim to support the demo building in reaching the challenging level of positive energy building (PEB) in a Nordic climate. It also studies the limitations that can be faced in achieving this target. A quantitative techno-economic analysis of the PEB is carried out to estimate the performance that includes analysis of energy matching and life cycle cost, using the above mentioned technologies with different approaches. The analysis includes assuming a physical boundary and an extended virtual boundary of the building as well as including or excluding electrical plug loads due to appliances and lighting loads. The following is a summary of the key findings:

- Generally for the building to reach PEB level in Nordic climate, higher amount of renewable energy sources, planning of the building boundary and energy storage is needed.
- PVT is able to assist buildings in meeting the onsite demand, however wind turbine offers higher matching by reducing the electricity import and increase the export.
- It is important to identify the type of the building's loads that are included in the calculations as this effectively impacts the overall energy balance and reaching the PEB level.
- Specifically, the first step to reach PEB is to make the building highly energy efficient building with low energy demand. For the demo apartment building considered in this study, the space heating load is around 15.4 kWh/m²/yr, which is very low compared to the old 1970 s buildings (i.e. around 129 kWh/m²/yr [52]) due to better insulation, windows and heat recovery system. The cooling load for the building is 2.36 kWh/m²/yr, which is quite low, as in general summers are short and not very warm in the Nordic climate. On the other hand, the domestic hot water load is around 42.1 kWh/m²/yr, which is high due to its high supply temperature (around 60 °C) and its recirculation losses.
- The PEB level is very challenging to be achieved when the energy system is consisted of limited PVT area due to roof area limitations and all the loads of the building is considered including the plug loads due to appliances and lighting. For the studied case, the investment cost in the energy system is around 47–62% of the LCC. The investment cost on the energy system varied between 50 €/m² – 75 €/m². The energy operational cost is relatively high and varied from 56 €/m² – 46 €/m².
- Excluding the plug loads in the above mentioned system, the building can reach the PEB level. For the studied case, the investment cost in the energy system is high, around 88–100%

of the LCC, and the operational cost of energy is low and there could be a positive cash flow due to larger export of electricity than import. The energy operational varied from 6.5 €/m² – (–0.3 €/m²). The investment cost on the energy system varied between 50 €/m² – 75 €/m².

- The PEB status is achievable with plug load included in the calculations when the building boundary is extended as a virtual boundary outside the physical boundary of the building. In this virtual boundary, wind turbines, extended shape of the building, and more PVT can be added to meet all the demands of the building. In this case, a very large area of the PVT, around 1600 m², or alternatively 75 kW of wind power together with 400² PV area, are needed for the studied building. In this scenario, the investment cost in the energy system is around 62–91% of the LCC and the energy operational cost is low in this case. The energy operational varied from 46.3 €/m² – 12.1 €/m². The investment cost on the energy system varied between 75 €/m² – 131.2 €/m².
- The borehole efficiency is low varying between 30 and 50 % depending on the boreholes geometry. Instead, one alternative can be to export the surplus heat to neighbouring buildings as a solution when the temperature level is suitable as part of energy sharing in a small community.
- The energy matching analysis of the studied case showed that:
 - When the PVT area is 400 m², including the plug loads and keeping the physical boundary, the onsite energy fraction (OEF) and the onsite energy matching (OEM) reach around 63% and 66%, respectively.
 - When the PVT area is 400 m², excluding the plug loads and keeping the physical boundary, the OEF and the OEM reach around 95% and 16%, respectively.
 - When wind turbines (75 kW) with 400 m² PVT or PVT (1600 m²) is added in the virtual boundary and the plug loads are included, the OEF reaches around 69 or 80% and the OEM reaches around 31% or 48%, depending on the type of renewable energy source.,
 - Generally, adding wind generation to the building increases the matching features due to higher availability of wind around the year compared with solar-based generation, PVT in this case. Therefore, it is important to optimize the system components' types and capacities in order to maximize the onsite-energy fraction and onsite-energy matching.
- The energy system cost is generally low compared to the building cost, i.e. around 1.2–4.3% of the building cost depending on the energy system design and the boundary. The building cost is

averaged around 4000 €/m² in Urban areas of Finland and average energy system cost is around 74 €/m²–171 €/m². Therefore, with a small additional investment, the building can be a PEB.

This research reveals that it is challenging for single apartment buildings to be PEB in the Nordic climate. It is even difficult to reach the Net ZEB level for the apartment buildings when all the demands are included in the energy balance calculations, however when plug loads are excluded, the Net ZEB or PEB levels could be reached depending on the boundary of the building. Possible way to reach PEB level is to put together such buildings within a large scale of a community of buildings connected in a local grid. This will facilitate providing larger area to install various capacities of energy generation and storage units and also share energy with the other building in the community. These PEB communities can support in creating a positive energy district (PED). Experimental validation is required in the future and this study would provide basic calculations for the demo building. Moreover, with the change in climate in the future the energy demands and indoor comfort requirements for the buildings may change, and this scenario can be studied in the future work.

This study also reveals that there should be a common agreement on the definition, boundary and the type of the loads that are considered in the calculations towards achieving a PEB. As discussed in section 6.2–6.3 it is important to identify the PEB boundary and loads at the initial stage, as this can impact the calculations for the generation and demand that has to be included in the calculations. The identification of the building's boundary can be influenced by many factors such as the geography of the city, the location of the building, local regulations, building type and construction, the available energy infrastructure, market and financial model, environmental conditions and cost, etc. For example, a PEB could include PVT and wind turbines located in the virtual and physical boundary of the building together in the extended boundary. This space can also be used to install energy storages in the form of heat, electricity or hydrogen. Solutions with energy storage will reduce the imported energy, increase the matching factors and support the building to reach PEB levels when large capacity of the renewable energy sources are integrated. Land and space use by the energy storage such as tank is also a significant issue in the building. Some of the challenges related to the virtual boundary can be the issues of extra land cost, ownership issues, rental cost, regulations or any other policy issues. Another aspect that can be considered is to buy shares in renewable energy generation plants (such as wind farms, etc.), which can be considered as using onsite renewable energy that can compensate the imported. However, these issues have to be identified and discussed at the early stages of the project to ensure best approach to reach the PEBs level.

CRediT authorship contribution statement

Hassam ur Rehman: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ala Hasan:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Francesco Reda:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of Competing Interest

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

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