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Energy and exergy analysis of prosumers in hybrid energy grids

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ABSTRACT

Surplus energy can be a recurrent phenomenon in zero-energy buildings (ZEBs) with onsite generation systems, usually resulting in the export of excess electricity. Yet, converting electricity into heat and exporting it could improve the overall energy balance. This study analyses the energy and exergy performance of a Finnish nearly zero-energy building (nZEB) as a heat and electricity prosumer, and proposes alternative energy topologies to improve energy and exergy levels, primary energy demand and CO2 emissions. The results show that increasing the installed capacity of the photovoltaic systems would lead to zero energy, exergy, emissions and a balance of primary energy. However, by instead using the surplus electricity to drive a heat pump and export heat, the currently installed capacity would lead to a net energy export of over 4000 kWh/a. Thus, energy conversion could significantly enhance the contribution from heat and electricity prosumers to smart energy grids, though not without affecting other criteria. Two management strategies arise: favouring heat export improves the net energy and CO2 emissions reduction but lessens the net exergy, while favouring electricity export improves the net exergy and primary energy reduction. The findings highlight that energy conversion can enhance nZEB performance and its exchange with hybrid grids.

KEYWORDS

CO2 emissions; exergy; nearly zero-energy buildings (nZEBs); net zero; renewable energy; sustainable buildings

Introduction and background

With the adoption of the Energy Performance of Buildings Directive (EPBD), the European Union has agreed that member states will ensure that all new buildings will be nearly zero-energy buildings (nZEBs) by 31 December 2020 (EPBD, 2010; Visscher, Meijer, Majcen, & Itard, 2016; Ferreira, Almeida, Rodrigues & Silva, 2016). This task requires excellent energy efficiency, reduced energy demands, and the inclusion of significantly enhanced onsite renewable energy and advanced storage systems (Cao, 2016; Judson & Maller, 2014). The combination of these actions may lead to periods when there is a surplus of onsite generated energy that should be properly managed, since zero-energy buildings (ZEBs) connected to grids should be able to operate in synergy with them (Cao & Sirén, 2015; Sartori, Napolitano, & Voss, 2012). Moreover, the use of components such as heat pumps links different forms of energy (thermal and electrical); hence, a need arises to study nZEBs as hybrid energy systems (Coninck, Baetens, Saelens, Woyte, & Helsen, 2014; Nord, Qvistgaard, & Cao, 2016; Wemhoener, Haessig, Wyss, & Staubli, 2016). Besides, the need for heat at different temperatures (e.g. for space heating, air-handling unit (AHU) heating and domestic hot water (DHW)) further complicates the management of thermal resources. Thus, an energy-based analysis could be complemented by an exergy analysis, which may give additional insights into the supply and demand management of the system.

Exergy is the maximum work potential in an interaction between a system and its surrounding environment; if the system is in equilibrium with the environment, the exergy of the system is null (Hepbasli, 2012; Toríó, Angelotti, & Schmidt, 2009). While energy is the most common approach to measure work, exergy offers information about the quality of the energy and whether it could be better exploited. Exergy thus gives deeper insight into the efficiency of a process. No longer is efficiency only a measure of units of energy in versus units of energy out. Instead, it is reframed as how useful are the units of energy in versus how...
useful are the units of energy out. Two comprehensive reviews on exergy analyses of the built environment, by Torio et al. (2009) and Hepbasli (2012), identify the fact that exergy can be used to show what influence a modification of the process or the components has on the overall performance of the energy system. This potential can be better observed through the exergy method rather than through energy balances. Most of the reviewed studies focused on one or two heating systems, and those that analysed several systems did so on a case-by-case basis so the interactions between different systems were not studied.

The dependencies between supply and demand systems were investigated by other authors. Terés-Zubiaga, Jansen, Luscuere, and Sala (2013) conducted a dynamic exergy analysis for the different energy supply configurations of a social dwelling, such as heat pumps, combined heat and power (CHP), and solar panels. It was concluded that the exergy approach complements and gives a more rational analysis than if the analysis is solely based on energy, since it indicates the ideal thermodynamic improvement potential.

Kılıç (2012) drew key lessons from the case study of a premier net-zero-energy building in Ankara, Turkey. The energy technologies in the building were integrated to match the exergy levels across the supply and demand sides, so as to put forth a value chain with ‘exergy-aware’ features. Kılıç also analysed the effect of this feature on CO₂ emissions in the scale of building communities, thus including electrical and heating grids in the energy system; economic profitability or primary energy consumption were not addressed.

Razmara, Maasoumy, Shahbakhti, and Robinett III (2015) developed a model-predictive control technique based on the exergy model for a building, aiming to minimize exergy destruction in the heating, ventilation and air-conditioning system. When compared with predictive control based on energy, the exergy-based control reduced exergy destruction and saved more energy.

Some gaps in the literature were found, though. Exergy studies that focus on exchange with a heating grid have so far been limited to exchange in a single direction: the grid supplies heat to the building. Only Kılıç (2012) addressed bidirectional exchange, yet the analysis focused on the reduction of CO₂ emissions and did not explore its effects on the overall efficiency of the system, nor its economic profitability. Still, residential buildings with the capability to export heat are bound to become a common research topic as sustainability in heating grids continues to evolve.

The ever more strenuous regulations for the built environment drive the evolution of energy and buildings research (Summerfield & Lowe, 2012). As such, an emerging perspective for addressing sustainable energy use is the study of smart energy systems (Lund et al., 2014). These types of system rely on integrating smart electricity grids, smart heating grids, and other means of energy transport and storage in order to increase the use of fluctuating energy sources, such as wind and solar power, as described by Mathiesen et al. (2015). These authors also stress the need for smart grids that harmonize the exchanges with ‘suppliers, consumers, and those that do both’. The latter, also named prosumers, were studied in detail regarding their role in the electricity sector, but only limited studies exist about prosumers in the heating sector. Brange, Englund, and Lauenburg (2016) present a case study of small-scale heat prosumers in Malmö, Sweden, where excess heat from cooling systems can be exported to smart heating grids. They show that even if the presence of heat prosumers in a system comes with challenges, it has significant potential to improve the energy balance.

Overall, exergy-based analysis seems to be consolidated as a fruitful strategy for measuring and improving the energy performance of the built environment, while the smart energy grid is an emerging topic that is gaining relevance in the scientific community and one which will certainly spark an extensive amount of research. This offers possibilities to apply existing methodologies to upcoming and unconventional energy systems. For instance, no exergy-based analyses of single-family houses with bidirectional heat and electricity exchange with district grids has been reported in the literature. Such a study could aid in reaching a better understanding of the connectivity options between nZEBs and open heating grids, such as the one in Stockholm or that to be built in Finnoo, in the Helsinki Metropolitan area, where the buildings will have the ability to export heat to their heating grid at different temperature levels.

Thus, the aim of this study is to assess the energy and exergy performance of different system topologies including several generation components, onsite storage and bidirectional exchange capacity with heating and electrical grids, based on the model of an existing residential nZEB. The study aims to answer the research question:

What is the impact of energy conversion and bidirectional heat and electricity exchange with distribution grids on the performance of a single-family building?

Moreover, it aims to identify if the performance of the building is affected by the temperature of the heating grid, and how different performance criteria react to energy conversion and bidirectional heat and electricity exchange strategies.

The novelty of this paper is as follows:

- Exergy and energy balances that consider bidirectional exchange with heating and electricity grids are
calculated. To the best of our knowledge, this is the first exergy-based analysis of heat and electricity prosumers in single-family buildings.

- The effect of heating grid temperatures on the exergy and energy balances of a residential heat and electricity prosumer is studied. The authors perform a dynamic analysis that considers the operating temperatures of the heat carriers so as to determine whether export is possible and, if so, how much exergy and energy can be exported.
- Strategies to reach zero exergy, energy, primary energy and/or emissions are presented. It is shown that prioritizing the export of heat or electricity can benefit or main these criteria.

Finally, the application potential of this investigation is important: detached and semi-detached houses constitute roughly 40% of the building stock in Finland, numbering over 1 million dwelling units (Statistics Finland, 2015b). The analyses presented here are exclusive of embodied energy impacts related to the reviewed systems, and are within boundaries set by the legal Finnish regulatory framework. Nevertheless, the results obtained could be used as a reference for comparison in the design of buildings in this country, with aims to reach net-zero or even net-positive buildings (Cole & Fedoruk, 2015). Moreover, these results may serve as benchmark for the development and integration of heat and electricity prosumers in other Nordic countries. Yet it is clear that other obstacles are present on the road towards a sustainable built environment, such as having the right policies (Sunikka, 2006) or developing functional typologies of the building stock (Kaasalainen & Huuhka, 2016).

Methodology

To evaluate the system’s performance, two sets of indicators with different scopes were established. The first and most straightforward were the net-energy and net-exergy exchanges. To address the EPBD and European Union long-term goals, a second group of indicators, including primary energy consumption and CO2 emissions, is included. This indicators will be calculated for (1) real operation of an existing building, (2) a simulation model of the same building and (3) a set of case studies with different energy exchange and conversion capabilities. For simplicity, in this text the term energy refers to site energy, unless stated otherwise (e.g. primary energy). The term quality factor (QF) used throughout refers to the ratio between exergy and energy, calculated as:

\[ QF = \frac{X}{E}, \quad (1) \]

where \( X \) and \( E \) are the exergy and energy in a given energy system or process respectively.

Energy analysis

The energy demand is calculated with a multi-zone building model – along with the energy generation, conversion and storage components. The weather data are on a time resolution of one hour and correspond to the year 2014. Outdoor temperature and solar radiation were measured onsite, whereas the rest of the weather data consist of values measured by the Finnish Meteorological Institute (FMI). The contribution from occupants is calculated based on the National Building Code of Finland (NBCF), with 125 and 62.5 W per adult and per child respectively. The internal gains originated by lighting and domestic appliances are based on the measured data. The generated surplus from the PV panels can be directly exported to the electrical grid or used to generate heat and export it. In the former case the inverter losses must be accounted for, but no further considerations are required. The conversion of electricity into heat is done by the virtual components to be described in the homonymous subsection.

Figure 1 shows the boundary defined for the energy analysis of Villa ISOVER, the studied building, as well as its energy topology. For the purpose of the energy calculations, all the onsite generation and conversion components are within the system boundary.

The net electric energy exchange and net heat exchange with the grids – \( E_{El,net} \) and \( Q_{net} \) respectively – are calculated as:

\[ E_{El,net} = \int_{t=1}^{t=n} [\dot{E}_{El,imp}(t) - \dot{E}_{El,exp}(t)] dt, \quad (2) \]

\[ Q_{net} = \int_{t=1}^{t=n} [\dot{Q}_{exp,ST}(t) + \dot{E}_{El,exp,Q}(t) - \dot{Q}_{imp}(t)] dt, \quad (3) \]

where \( \dot{E}_{El,imp} \) and \( \dot{Q}_{imp} \) are the imported electric and heating power respectively; \( \dot{E}_{El,exp} \) and \( \dot{E}_{El,exp,Q} \) are the exported electricity surplus in the form of electricity and heat respectively; and \( \dot{Q}_{exp,ST} \) is the exported heat surplus from the solar thermal (ST) collectors. \( \dot{E}_{El,exp,Q} \) represents the output from the components that convert surplus electricity into heat. While there is no export of heat in the existing topology, it was included in the equations for the case studies proposed below. The net energy exchange, \( E_{net} \), which amounts the electricity and heat exchange with the grids, is calculated as:

\[ E_{net} = E_{El,net} + Q_{net}, \quad (4) \]

and it illustrates how close the building is to reach a net zero-energy exchange with the hybrid grid.
Exergy analysis

The focus of this study is on the performance of a system with different topologies. The efficiency of each component is not being investigated, but rather how each component contributes to the overall efficiency of the system. Therefore, the system boundary is established on a similar basis as the ‘physical boundary’ approach as described by Torío and Schmidt (2010). That is, the first transformation of solar irradiation into other forms of energy does not happen within the system boundaries: using this approach, the output from photovoltaic (PV) panels and ST collectors is taken as primary energy. The conversion of electricity into heat takes place within the system boundary. Following the recommendation of Torío and Schmidt (2011), the surrounding outdoor air was established as a reference. Since the fluctuation of the outdoor air temperature is detrimental to the clarity of the results in this study, a constant value was established for the exergy calculations: 6.7°C, the average outdoor air temperature onsite in 2014. The influence of indoor air exergy is neglected in this study, as indoor temperature levels are the same in all the studied cases.

The heat export depends on the temperature of the transport fluids as this determines whether or not the heat-transfer process to the heating grid is possible. For this process, it is assumed that an ideal heat exchanger is connected to the heating grid on one side and to the building system on the other side.

The net electric exergy exchange and net heating exergy exchange – $X_{El}$ and $X_Q$ respectively – are calculated as:

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

and it illustrates how close the building is to reaching a net zero-exergy exchange with the hybrid grid. The expressions for the exergy of electricity and heat system components can be found in the Appendix in the supplemental data online.

Net primary energy and CO2 emissions

The net primary energy is calculated through weighting factors, $F_{PE}$, established by the Finland Ministry of the Environment (2011), whereas the factors for the equivalent CO2 emissions, $F_{CO2}$, are published by Statistics Finland (2015a). Both sources are specific to Finland. For energy generated onsite by PV panels, heat supplied by ST collectors and heat extracted from the ground, $F_{PE}$ and $F_{CO2}$, are assumed to be zero. Any exported energy is assumed to replace energy production by the utilities;
thus, $F_{PE}$ and $F_{CO2}$ for exported heat and electricity are assumed to be the same as those for the grids. Table 1 shows the factors used in this study. Note that electricity has a higher primary energy factor (i.e. more units of primary energy are required to produce each unit of energy used in the building) but lower emissions than district heating, which might be unexpected. This is a consequence of the energy contribution in Finland from nuclear power, which provides nearly 30% of the country’s electricity. As indicated in European Standard CEN 15603:2008, electricity from nuclear power plants has a primary energy factor of 2.80, and an equivalent emission coefficient of 16 g/kWh. The validity of the factors used in Finland is beyond the scope of this study and, given their sources, they are considered to be valid for the purposes of this publication. The net primary energy and CO2 emissions are calculated as:

$$PE = E_{El,net} \cdot F_{PE,El} + Q_{net} \cdot F_{PE,Q},$$

$$CE = E_{El,net} \cdot F_{CO2,El} + Q_{net} \cdot F_{CO2,Q},$$

where $PE$ is the net primary energy replaced (positive values) or consumed (negative values); and $CE$ are the emissions replaced (positive values) or generated (negative values). Note that the time scale of the analysis is one year – this is not the life cycle of the system. The primary energy consumption and emissions derived from the manufacturing, transport or disposal of the system components are beyond the scope of this study.

### Building description and case studies

#### Overall description of the building

Villa ISOVER is a joint project between ISOVER and FORTUM, conducted to test the performance of a single-family zero-energy house and its interaction with the electrical grid. The two-storey building is located in Hyvinkää, southern Finland, and is inhabited by a family of four. Its energy system integrates PV panels, ST collectors, a ground-source heat pump (GSHP) and an AHU; it has no connection to an external heating network as the GSHP and ST collectors fulfil the heat demand. A monitoring system keeps track of several heat and electricity measurements, such as PV generation, electricity exchange with the grid or heat generation by the solar collectors and GSHP. Further, solar radiation, and indoor and outdoor temperatures are monitored. Further information and visualizations of the building are available online.

#### Location and weather

Hyvinkää is located in Uusimaa, the southernmost region of Finland. The site has a subarctic climate under the Köppen–Geiger climate classification system, which is a climate characterized by brief, cool summers and long winters with low temperatures and clear skies (Pidwirny, 2011). Solar radiation on a horizontal surface roughly corresponds to 1000 kWh/(m²·a) (Faninger-Lund, 2002). The measured average outdoor temperature during the year was 6.7°C; the total annual heating degree-days in Helsinki (just as is the case for the whole of Uusimaa) were 3464 (Finnish Meteorological Institute, 2016).

#### Building parameters

The NBCF establishes binding technical regulations and instructions concerning ventilation, airtightness, indoor temperatures and heat-transfer coefficients, among other parameter requirements: Villa ISOVER fulfils the required conditions, ultimately satisfying the building’s total energy consumption limit for new buildings established in decree D3 (Finland Ministry of Environment, Department of the Built Environment, 2011). Table 2 compiles some key building features, and indicates whether the value of each feature is based on the building plan, based on the NBCF, taken from nominal values by equipment manufacturers, or measured in the inhabited building. Measured values correspond to the year 2014.

The measured DHW heat demand is atypically low for a single-family house compared with the estimated value of 35 kWh/m²·a given by the NBCF (Finland Ministry of Environment, 2011). No signs of malfunctioning were present in the instrumentation, so it is assumed that the inhabitants have a low demand for DHW.

The monitoring system in the building records the electricity demand, generation and export, which indicates the total electricity consumption destined for non-thermal purposes (e.g. for domestic appliances and lighting), allowing for an estimate of their portion of the internal gains. The combined gains from lighting and domestic appliances obtained from the electricity consumption give an average of 2.2 W/m², which is in line with the 2.6 W/m² suggested for internal heat load calculations in the NBCF.

#### Building energy services and instrumentation

The building’s space heating and DHW needs are covered by the GSHP and ST collectors. A 128 m borehole
heat exchanger is connected to an NIBE F1145-6 GSHP. The flat-plate ST collectors NIBE FP 215 have a total area of 6 m². Both systems feed an NIBE VPAS 300/450 accumulator hot water storage tank (HWST), primarily designed to be connected to a heat pump and ST collectors. It is a tank-in-tank component, with an inner 300-litre reservoir intended for DHW, and an outer 450-litre reservoir for space-heating needs. A schematic representation of the system is shown in Figure 1. The system is controlled by the GSHP: the circulation pump to the ST collectors is started when the temperature difference between the collectors and the bottom of the HWST reaches 8°C and stops when it falls under 4°C; if solar energy is not available or it is insufficient to cover the heat demand, the GSHP starts operating. An Enervent Pandion ventilation unit covers the ventilation needs. There are no cooling systems in the building.

Onsite electricity generation is available through 72 copper indium selenide (CIS) solar modules PowerMax STRONG, with a nominal power of 130 Wp each, covering a total area of 79 m² (each panel having an area of 1.09 m²). The PV panels and the solar collectors are at a 25° tilt angle, facing south. There is no electricity storage system in the building.

The electricity demand in Villa ISOVER is covered by the PV system and energy imported from the grid. The electricity demand of the GSHP is measured with an EM23 DIN energy meter, and the electricity demands of the rest of the heating system and ventilation unit are measured with EM10 DIN energy meters. All heat transport processes are measured with Sharky 775 energy meters. The error percentages of the Sunny Boy 3000HF, EM23 DIN, EM10 DIN and Sharky 775 measurement instruments are ±3%, ±1%, ±1% and ±2% respectively.

### Virtual components

System configurations are proposed in order to assess the performance of the building under different scenarios. They are based on variations of the building energy services, and may include components that do not exist in the building. These components (hereafter described as virtual) allow the simulation of different energy generation and exchange profiles.

For the conversion of electricity into heat, two virtual components are considered. One consists of a tankless electric water heater, which could input the excess electricity as heat into a heating grid with 100% conversion.
efficiency. A second approach consists of the use of a hypothetical air-source heat pump with a constant coefficient of performance (COP) = 2. An outlet temperature of 60°C is set based on specifications of commercially available products by the same manufacturer as the GSHP. The NIBE F2030 and F2040 offer outlet temperatures of 58 and 65°C, respectively; an intermediate value was chosen.

Energy sinks are required for the export of the surplus generated energy. In the case of heat, it is necessary to characterize the temperatures and dynamic behaviour of the energy sink in order to calculate whether exporting is possible and, if so, the exergy of heat that could theoretically be exported. Furthermore, the QF of imported heat will also affect the exergy balance of the system. Two heating grids were designed for this purpose, each with a supply and a return pipeline. One grid represents the conventional heating grid in Finland, while the other represents a low-temperature district heating grid. This will allow a comparison to be made of the potential for exergy exchange of the building between two grids at different exergy levels. Moreover, low-temperature district heating grids, among other benefits, facilitate the inclusion of low-temperature energy sources such as geothermal plants, heat pumps and residual or excess process heat (Lund et al., 2014; Energy Development and Demonstration Program, 2014). Thus, a low-temperature district heating grid could allow more heat export from the ST collectors and virtual heat pump than a conventional heating grid. The dynamic behaviour of the temperature for both options is modelled as one sinusoidal cycle in the simulated year, reaching the maximum and minimum temperatures in the middle of winter and summer respectively, as shown in Table 3. The feed-in principle for export from the ST and the hypothetical heat pump is based on feed-in return → return, where water is taken from the return line of the heating grid, heated and reinjected into the same return line, as described by Schubert (2012).

From here on, the heat transport fluid on the virtual heating grid will be referred to as the primary fluid and the heat transport fluid on the building side as the secondary fluid. In all cases, the temperature of the primary fluid is considered to remain unaffected by the heat-transfer process. Furthermore, if the temperature of the secondary fluid is not at least 5°C higher than that of the primary fluid, the heat export cannot take place. In the case of heat export by the ST collector, a minimum return temperature of 55°C is set; this temperature ensures that the heat export does not lead to an energy deficit in the HWST.

### Case studies

Three sets of energy topologies with different energy conversion and exchange capabilities were designed in order to compare their performance: cases 1–3. Each case is modelled with growing PV or growing ST (e.g. case 1-PV and case 1-ST), and each case includes two sub-cases (e.g. case 1-PV-El and case 1-ST-Q). In sub-case El, the electricity surplus is directly fed into the electrical grid without prior conversion. In sub-case Q, the electricity surplus is either converted to heat or used to drive a heat pump (depending on the energy topology), and the heat is fed into the heating grid. The need for an additional heat pump arises since running the GSHP during summer, when most of the surplus energy generation takes place, would reduce the ground temperature and this would lead to a severe drop in the COP of the GSHP. Table 4 summarizes the main features in each case study.

In case 1, the system topology is similar to that existing in the building, but the installed generation capacity was increased: in case 1-PV the installed peak power of the PV system was increased in steps of 1.04 kWp (i.e. the capacity of eight panels) from 9.36 kWp (79 m²) to 16.65 kWp (140 m²), while in case 1-ST the installed area of the ST collectors was increased in steps of 2 m² (i.e. the area of one collector) from 6 to 20 m². Furthermore, two options are analysed regarding the export of the surplus electricity as it can be directly fed into the electrical grid (sub-case El) or converted to heat and fed into a heat sink by means of a virtual direct electric heater (sub-case Q). It is assumed that this component would be able to reach the temperature of any line in the heating grids.

In case 2, the GSHP is not operated; the heat demand of the building is covered by the ST collectors and with heat imported from the virtual district heating grids described above. The ST collectors have the option to export heat to the heating grid. As in case 1, two options for increasing the generation capacity of the PV system and the ST collectors – 2-PV and 2-ST respectively – were simulated. Further, the surplus electricity can be directly fed into the electrical grid (sub-case El) or converted to heat and fed into the heating grids by means of the virtual heat pump (sub-case Q). The decision not to let the virtual heat pump feed heat to the building is based on the reasoning that the virtual heat pump is assumed to be operated exclusively with surplus energy.

### Table 3. District heating temperature ranges (°C).

<table>
<thead>
<tr>
<th>Supply</th>
<th>Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional grid</td>
<td>115</td>
</tr>
<tr>
<td>Low-temperature grid</td>
<td>70</td>
</tr>
</tbody>
</table>

generated by the PV system, which indicates that there is an abundance of solar radiation. Thus, the ST collector would probably be operating too and having both the virtual heat pump and the ST collector feed the HWST would be detrimental to the operation of the ST collector.

In case 3, the heat demand of the building is covered by the ST collectors and GSHP. The ST collectors can export heat to the heating grid. As in cases 1 and 2, two options for increasing the generation capacity of the PV system and ST collectors – 3-PV and 3-ST respectively – were simulated. Additionally, sub-cases El and Q were implemented as described for case 2.

Simulation tools

The simulations were conducted on TRNSYS 17, a commercial energy simulation software package intended for the calculation of transient systems, with the help of tools and add-ons such as TRNSYS3D, TRNBuild and TRNFlow. The time step for the simulation was 0.25 hours. The measured generation and demand, as well as the weather data, were in a time resolution of one hour; a shorter time step was used in the simulation to favour convergence and stability in the models.

Results

Performance of the existing topology

Figure 2 shows the measured demand and supply of energy and the calculated demand and supply of exergy in the building for 2014. The label Heat. Sys. refers to the electricity consumption of the GSHP and other components of the heating system. In the energy balance, the

<table>
<thead>
<tr>
<th>Case</th>
<th>Photovoltaic (PV) capacity (kWP)</th>
<th>Solar thermal (ST) capacity (m²)</th>
<th>Ground-source heat pump (GSHP)</th>
<th>Sub-case</th>
<th>Import from the electrical grid</th>
<th>Export to the electrical grid</th>
<th>Export via the virtual direct electric heater</th>
<th>Export via the virtual heat pump</th>
<th>Corresponding result figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-PV</td>
<td>9.36, 10.40, 11.44, 12.48, 13.52, 14.56, 15.60, 16.64</td>
<td>6</td>
<td>✓</td>
<td>Electricity (El)</td>
<td>✓✓✓✓✓✓✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓✓</td>
</tr>
<tr>
<td>1-ST</td>
<td>9.36</td>
<td>6, 8, 10, 12, 14, 16, 18, 20</td>
<td>✓</td>
<td>El</td>
<td>✓✓✓✓✓✓✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓✓</td>
</tr>
<tr>
<td>2-PV</td>
<td>9.36, 10.40, 11.44, 12.48, 13.52, 14.56, 15.60, 16.64</td>
<td>6</td>
<td>–</td>
<td>Q</td>
<td>✓✓✓✓✓✓✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓✓</td>
</tr>
<tr>
<td>2-ST</td>
<td>9.36</td>
<td>6, 8, 10, 12, 14, 16, 18, 20</td>
<td>–</td>
<td>El</td>
<td>✓✓✓✓✓✓✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓✓</td>
</tr>
<tr>
<td>3-PV</td>
<td>9.36, 10.40, 11.44, 12.48, 13.52, 14.56, 15.60, 16.64</td>
<td>6</td>
<td>✓</td>
<td>Q</td>
<td>✓✓✓✓✓✓✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓✓</td>
</tr>
<tr>
<td>3-ST</td>
<td>9.36</td>
<td>6, 8, 10, 12, 14, 16, 18, 20</td>
<td>✓</td>
<td>El</td>
<td>✓✓✓✓✓✓✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓✓</td>
</tr>
</tbody>
</table>

Figure 2. Electricity (left), heat (middle) and exergy (right) balances of Villa ISOVER based on the measured data.
total supply exceeds the demand by approximately 11%. This can be explained by three primary reasons: first, the heat demand from the ventilation system has not been measured; second, the heat losses in the HWST are not measured; and third, there may be measurement errors. Taking this into consideration, the energy balance seems fairly correct. Only 1463 kWh out of the 6611 kWh generated by the PV system were consumed onsite: 5148 kWh were exported to the grid and 7784 kWh were imported to cover demand. Thus, the net exchange with the electricity grid was a demand of 2636 kWh, yielding an overall average of 15 kWh/m².

The uncertainty values for the measured data were calculated based on the error of the instruments described above. Based on the rules for error propagation, the uncertainty values are ±2.3% and ±1.7% for electricity supply and demand respectively, and ±1.7% and ±1.8% for heat supply and demand respectively.

Nominal operating temperatures, set-point temperatures and/or estimations were used for the calculation of the exergy balance. Thus, the values in the exergy balance are for illustrative purposes and must be used with caution. The three imbalance reasons mentioned for energy apply to the exergy balance as well. The results seem reasonable, with QFs of 0.05 for the floor heating demand and 0.15 for the DHW demand, which are in agreement with Schmidt (2009). Further, it is expected that the exergy supply exceeds demand as part of the exergy is destroyed in the heat transfer and energy-conversion processes according to the second law of thermodynamics. The net exergy import during the year was also 2636 kWh, since the entirety of the imported energy was supplied in the form of electricity, which has QF = 1. The most notable contrast with the energy balance is seen with the floor heating and GSHP, due to their low exergy factors.

The building had a net primary energy consumption of 25.6 kWh/m² and emissions corresponding to 440.2 kg CO₂, calculated based on the equations and factors given in subsection ‘Net primary energy and CO₂ emissions’.

Figure 3 shows the monthly energy balances for electricity and heat in 2014. Although there were large surpluses of electric power in several months, electricity had to be bought from the grid throughout the entire year. Further, the influence of the GSHP on the demand for electricity is visible and notably higher during the cold season. On the other hand, the chart on the right shows that the heat demand in the building is covered entirely by onsite generation, though the contribution from the ST collectors is relatively small.

According to the net energy and exergy exchanges in 2014, neither the zero-energy nor zero-exergy levels were reached, but the building is not far from reaching these goals. To do so, two main approaches could be suggested: to reduce further the energy and exergy consumption or to enhance the energy and exergy generation. The area of interest of this study is in the latter, as the authors’ aim is to explore energy conversion and exchange. The generation systems have the potential to reduce further the net energy and net exergy imports by (1) allowing the export of surplus heat from the solar collectors, and (2) enhancing the export of surplus energy from the PV system. Concerning the surplus energy from the PV systems, using electricity to generate heat could potentially increase the energy export, but this may involve significant exergy destruction. Thus, attention must be paid to the results obtained for both balances as improving one may compromise the other.

Base model and calibration

A model with the same system topology and generation capacity as the one in Villa ISOVER was designed based on the planned building features, as shown in Table 2. The energy and exergy balances resulting from this simulation can be seen in Figure 4.

When compared with the measured data in Figure 2, it can be seen that the floor heating demand is notably smaller in the simulation. Additionally, the power demand from the GSHP is significantly smaller than

![Figure 3. Monthly electricity (left) and heat (right) balances for Villa ISOVER, 2014.](https://example.com/figure3.png)
the measured data. In order to have simulation results closer to the measured data, the $U$-value of the external walls was increased from 0.09 to 0.17 – the value defined in decree D3 of the NBCF, the heat-recovery efficiency of the ventilation system was lowered from 76% to 70%, the COP of the GSHP was set as 3.36 (the average COP during 2014 in the measured data), and the set-point temperature was raised from 21 to 22°C.

Figure 5 shows the energy and exergy balances obtained from the calibrated simulation. The results are in closer agreement with the measured data. Note that the measured heat demand for DHW was atypically low. Detailed hourly and monthly DHW demand profiles for households in Finland are presented by Ahmed, Pylsy, and Kurnitski (2016); nevertheless, part of the aim of this study is to mimic Villa ISOVER’s energy demands in 2014, so measured data are given priority over derived or tabulated profiles. Thus, the measured hot water consumption in litres was used instead in the simulation model, which yielded a heat demand closer to that given in the NBCF. Furthermore, the measured data encompass all seasons throughout the year, and thus cover building behaviour under usual meteorological conditions in Finland. Based on these results, the model is considered to be a satisfactory representation of the building for the purposes of this study.

**Case studies**

**Net energy and net exergy**

Figure 6 shows the surplus electricity generation of the PV system in the calibrated and uncalibrated models for cases 1-PV, 2-PV and 3-PV, and the measured value and the surplus heat generation from the ST collector in the calibrated and uncalibrated models for cases 1-ST, 2-ST and 3-ST. As expected, for most cases the surplus increases linearly with the installed capacity. In case 1-ST the ST system can neither generate nor export any surplus, and thus has a constant value of zero. The curves indicate two aspects when comparing the calibrated and uncalibrated models. First, the values of surplus electricity and heat generation differ only slightly between the two models. Second, the surplus electricity and heat generation as a function of the installed capacity for both models show the same (linear) behaviour. The difference between the modelled surplus electricity generation and the measured value does not depend on whether or not the model is calibrated, as seen in Figure 6. This is because energy
generation from the PV system mostly happens during the summer season when the heating demand (and, thus, electricity consumption from the GSHP) is low, that is, when the calibration has the least influence on the results.

Figures 7 and 8 show the net energy exchange and net exergy exchange for cases 1-PV and 1-ST respectively. In addition, Figure 7 includes the net energy and net exergy for the uncalibrated model, as well as the net energy in the measured data. As in the existing energy topology, only the PV system can generate a surplus. For net exergy, it can be seen that it is influenced by the temperature of the line receiving the exported heat. As can also be seen in Figure 6, the curves of the calibrated and uncalibrated models have similar behaviour: vertical displacement can be seen, but the curves appear to have the same slope. Furthermore, the net energy and net exergy of the calibrated model are close to the measured value, as can be seen in the left and middle charts of Figure 7. Based on these premises, as well as on those derived from the analysis of Figure 6, here on only the results for the calibrated model are shown in the figures as no substantial difference between the models can be expected. From Figures 7–15, a line intersecting the horizontal axis indicates that a neutral condition is reached (e.g. the net energy is equal to zero).

Figures 9–12 show the net energy exchange and net exergy exchange for cases 2-PV, 2-ST, 3-PV and 3-ST, respectively. The temperature level of the virtual heating grid does not have a significant influence on the net energy, and thus no distinction is made between the grids on the charts on the left in Figures 7–12. For contrast, the results for each grid are shown separately for net exergy.

Net primary energy and CO₂ emissions

Figures 13–15 show the net primary energy and CO₂ emissions replaced for cases 1-PV and 1-ST, for cases 2-PV and 2-ST, and for cases 3-PV and 3-ST respectively. Since these indicators are exclusively for energy, no distinction needs to be made between the virtual heating grids.
Figure 8. Net energy exchange (left) and net exergy exchange (right) as a function of the photovoltaic (PV) capacity in case 2-PV. The 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 9. Net energy exchange (left) and net exergy exchange (right) as a function of the photovoltaic (PV) capacity in case 2-PV. The 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 10. Net energy exchange (left) and net exergy exchange (right) as a function of the solar thermal (ST) collectors’ area in case 2-ST. The 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 11. Net energy exchange (left) and net exergy exchange (right) as a function of the photovoltaic (PV) capacity in case 3-PV. The 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 12. Net energy exchange (left) and net exergy exchange (right) as a function of the solar thermal (ST) collectors’ area for case 3-ST. The 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 13. Net primary energy (PE) and CO₂ emissions required (negative) or replaced (positive) by exporting energy as a function of the photovoltaic (PV) capacity in case 1-PV (left) and as a function of the solar thermal (ST) collectors’ area in case 1-ST (right). The surplus electricity can be exported as electricity (El) or as heat (Q).
Discussion

Net energy exchange and net exergy exchange

Figure 7 shows that with a similar system topology to the one existing in Villa ISOVER, it could reach net zero-energy and zero-exergy exchange if the installed capacity of the PV system is increased to approximately 12.5 kW. On the contrary, as shown in Figure 8, increasing the area of the ST collectors would have little influence on the net energy exchange of the system if heat cannot be exported. Since the virtual electric heater has a conversion factor from electricity to heat equal to 1, exporting the surplus of electricity as either electricity or as heat makes no difference to the net energy exchange, but it does affect the net exergy exchange.

Figures 9 and 10 indicate that if, instead of having a GSHP, the heat were supplied by a district heating grid and the surplus electricity were converted to heat using the virtual heat pump and exported, the system would require approximately 11 kW of installed capacity of PV panels or 14 m\(^2\) of ST collectors to reach the net zero-energy exchange. However, if the surplus electricity were to be directly fed into the electrical grid, the net zero could not be reached. On the exergy side, this system topology has the significant advantage of importing low amounts of exergy from the heating grid. The figures show that for case 2, if electricity were to be directly exported to the grid, the net zero-exergy exchange would be reached with the installed PV capacity in both types of heating grid.

Figure 14. Net primary energy (PE) and CO\(_2\) emissions required (negative) or replaced (positive) by exporting energy as a function of the photovoltaic (PV) capacity in case 2-PV (left) and as a function of the solar thermal (ST) collectors’ area in case 2-ST (right). The surplus electricity can be exported as electricity (El) or as heat (Q).

Figure 15. Net primary energy (PE) and CO\(_2\) emissions required (negative) or replaced (positive) by exporting energy as a function of the photovoltaic (PV) capacity in case 3-PV (left) and as a function of the solar thermal (ST) collectors’ area in case 3-ST (right). The surplus electricity can be exported as electricity (El) or as heat (Q).
Figures 11 and 12 show that if the virtual heat pump were available and the solar collector were capable of exporting, the building would reach and surpass the net zero-energy exchange with the installed capacities of the PV system and ST collectors. The net zero-exergy exchange in case 2 could be reached with an installed capacity of 12.5 kW for the PV system, but it could not be reached by increasing the amount of ST collectors.

The effect of correlating the district heating temperature to the outdoor temperature was tested. The difference in the results amounted to less than 5%, with no significant change in the system performance.

**Net primary energy and CO₂ emissions**

The image on the left in Figure 13 indicates that increasing the size of the PV system could significantly offset the primary energy and CO₂ emissions, and that exporting electricity benefits the net primary energy more than the emissions, while exporting heat benefits the emissions more than the net primary energy. The image on the right indicates that increasing the size of the ST collectors has a minimal (if not negligible) effect on both criteria.

Figure 14 shows that using the surplus electricity to run the virtual heat pump has a beneficial effect on CO₂ emissions because a net heat export can be reached, and the emissions are higher due to electricity import. However, using the virtual heat pump is detrimental to the primary energy, as the system now has a larger net import of electricity, which has a primary energy factor larger than district heating. Nonetheless, both criteria can reach and surpass the horizontal axis in case 2-PV. However, if the surplus electricity is directly fed into the grid only the primary energy offset can be reached. For case 2-ST, a positive balance for CO₂ emissions can be reached when using the virtual heat pump. However, the other three curves cannot reach positive values.

As seen in Figure 15, in case 3 the system could offset emissions with the installed PV and ST capacities if the surplus were exported as heat. Or, it would be almost emission neutral if the surplus were exported as electricity. Furthermore, with an installed PV capacity of approximately 12.5 kW, the building could be primary energy neutral and emission neutral if the surplus were exported as electricity. Regarding case 3-ST, it can be seen that the building would not reach positive values for primary energy offset.

**Overall performance**

Table 5 summarizes the main system features which allowed reaching and/or surpassing the net zero exchange for each performance criterion. The features are as follows:

- **Energy and CO₂ emissions:** using the surplus electricity to drive a heat pump. The installed capacity for PV and ST in the building would be sufficient to reach a net energy export of over 4000 kWh/a and a net emissions replacement of approximately 1500 kg CO₂/a.
- **Exergy:** replacing the GSHP with a connection to the district heating grid. The installed PV and ST capacity in the building would be sufficient to reach the net-zero threshold.
- **Primary energy:** increasing the size of the PV system to 12.5 kW.

The results show two meaningful outcomes. It can be seen that heat pumps are detrimental to reaching the net zero-exergy exchange compared with plainly feeding electricity to the grid. However, heat pumps are beneficial for reaching the net zero-energy exchange thanks to their energy factors (or COPs), which are generally higher than 1. On the other hand, exporting electricity has higher benefits for the primary energy offset but lower benefits for the CO₂ emissions offset, while exporting heat has higher benefits for CO₂ emissions but lower benefits for the primary energy offset.

From these effects, two management strategies can be outlined:

- If the system favours the export of surplus in the form of electricity, the net exergy exchange and the primary energy offset are strongly improved, while the energy balance and CO₂ emissions are moderately improved.
- If the system favours the export of surplus in the form of heat, the net energy exchange and CO₂ emissions offset are strongly improved, the primary energy

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Net value</th>
<th>Photovoltaic (PV) capacity (kW)</th>
<th>Solar thermal (ST) area (m²)</th>
<th>Heat source</th>
<th>Heat export</th>
<th>Sub-case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy and emissions</td>
<td>4000 kWh (exported) and 1.5 tons CO₂eq (replaced)</td>
<td>9.4</td>
<td>6</td>
<td>Ground-source heat pump (GSHP)</td>
<td>Virtual heat pump</td>
<td>3-PV-Q or 3-ST-Q</td>
</tr>
<tr>
<td>Exergy</td>
<td>0 kWh</td>
<td>9.4</td>
<td>6</td>
<td>District Heating</td>
<td>–</td>
<td>2-PV-El</td>
</tr>
<tr>
<td>Primary energy</td>
<td>0 kWh</td>
<td>12.5</td>
<td>6</td>
<td>GSHP</td>
<td>–</td>
<td>1-PV-El</td>
</tr>
</tbody>
</table>

Table 5. Main system features for reaching the net-zero level for each criterion.
offset is moderately improved, and the net exergy exchange is strongly lessened.

Nonetheless, it must be mentioned that the two strategies can be merged, so part of the surplus electricity can be converted to heat and the rest can be exported as electricity. This is a feasible scenario, as a heat pump with a nominal power demand of a fraction of the installed PV system could be installed: a fraction of the surplus energy would then be converted into heat, increasing the emissions offset and net energy export, while exporting the remaining surplus electricity would increase the primary energy offset and net exergy export.

The study focuses on the energy exchange with the grids, so the system boundary was defined accordingly. Particularly, the solar radiation striking the PV panels and ST collectors, and the heat extracted from the ground are not accounted for in the calculations. This is in line with the regulatory framework, yet from a wider perspective these three energy influxes affect the energy, exergy and primary exergy balances of the system. Thus, these balances were recalculated for an exemplary case so as to provide an insight into how they affect the results. These energy flows (solar radiation and ground heat) are assumed to be free from emissions from an operational perspective, and thus this balance is not affected. Table 6 shows a comparison of the results for case 3-PV-Q – with the same capacity of PV and ST as currently installed in Villa ISOVER – with the ‘physical boundary’ (i.e. the boundary method adopted in this study) against the results with a ‘technical boundary’ (i.e. the boundary method that includes solar radiation and heat extracted from the ground). Readers are advised to consult Torío et al. (2009) and Torío and Schmidt (2010) for more information about these methods.

The results according to the technical boundary are roughly 75–87 MWh lower than those according to the physical boundary. The main reason for the drop is accounting for solar radiation on the PV panels and ST collectors: with their cumulative area of 85 m², they receive over 79 MWh of energy with over 75 MWh of exergy. Thus, the results under the technical boundary offer a wider perspective of the impact of the building.

| Table 6. Comparison of the results under different boundary methods for case 3-PV-Q exporting heat to the low-temperature grid, with 79 m² of photovoltaic (PV) panels and 6 m² of solar thermal (ST) collectors. |
|---|---|---|---|
| Method | Net energy exchange (kWh) | Net exergy exchange (kWh) | Net primary energy (kWh) |
| Physical boundary | 4233 | –6626 | –5422 |
| Technical boundary | –82,685 | –82,293 | –92,340 |

on the environment, whereas the physical boundary allows a narrowing of the focus into the energy system components. For the purpose of this study, the latter method is more suitable.

Figure 7 shows that the building would reach a zero-energy and zero-exergy level with the existing system topology if the installed PV capacity were 12.5 kW. For this case, a brief analysis of the matching capability of the building was conducted. The matching criteria of ‘onsite energy fraction’ (OEF) (representing the proportion of the onsite demand covered by onsite generation) and ‘onsite energy matching’ (OEM) (representing the proportion of the onsite generation consumed in the building system rather than being exported or dumped) were calculated for electricity and heating energy forms based on the extended onsite matching indices developed by Cao, Hasan, and Sirén (2013). Table 7 shows the calculated extended matching indices for electricity, i.e. OEF and OEM, and for heating, i.e. OEFh and OEMh. Exporting the surplus electricity directly into the electrical grid leads to low values for OEF and OEM. On the other hand, converting the surplus electricity into heating before exporting it leads to higher matching capability in the building. Overall, there is significant room for increasing the self-consumption of energy.

| Table 7. Matching indices for the simulated case with net-zero energy and exergy levels. |
|---|---|---|---|---|
| Sub-case | OEF | OEFh | OEM | OEMh |
| 1-PV-EI | 0.11 | 0.70 | 0.11 | 1.00 |
| 1-PV-Q | 0.53 | 0.70 | 1.00 | 0.53 |

Conclusions

The cold climate in Finland is a strong antagonist in the race to reach energy neutrality in buildings. Villa ISOVER had a significantly low level of net energy consumption in 2014 at 15 kWh/m²/a, but ultimately did not reach the planned goal to be a ZEB. By increasing the installed PV capacity to 12.5 kW, the building could reach zero energy, zero exergy, zero primary energy demand and zero CO₂ emissions, as seen in case 1-PV. One more option to reach the zero-energy level is to use the surplus electricity to operate a heat pump, and thus benefit from an energy factor. With this strategy, the building could be a net energy exporter with the existing capacity of the PV system, as seen in case 3. This would also notably reduce its CO₂ emissions and moderately reduce the primary energy consumption. If exergy is to be prioritized, any conversion of electricity into heat must be avoided, such as using electric heaters or heat pumps.
Smart hybrid grids with bidirectional energy exchange would facilitate reaching zero-energy and zero-exergy levels in residential buildings in Finland. As seen here, there is significant potential: as much as 4000 kWh/a could be exported by a heat pump with the installed PV capacity. This quantity is roughly 40% of the heat that the studied building would import from the heating grid to satisfy its heating and DHW demand. While bidirectional exchange was implemented on several electrical grids, reaching an agreement between users and heating grid operators is a pending task. The potential to make use of surplus heat might help to build a bridge between the needs of the parties involved.

To transform the current energy system into a fully sustainable system we need to harmonize the energy prosumers – be they heat prosumers, electricity prosumers or both. This study provides a qualitative indication of the role of heat and electricity residential prosumers in the smart energy grids by exploring the use of conversion technologies and it gives an insight into the energy quality that could be provided. With the diverse ongoing projects of smart energy systems in Nordic countries, these results could assist in the planning of a distributed generation scheme, with consideration of the energetic and exergetic contribution of the prosumers. This could aid in the decentralization process of heat and electricity generation, giving end users the opportunity to be active players in the energy grids while enhancing the synergy of the system.

The authors acknowledge the importance of an economic analysis to identify whether the proposed configurations could represent attractive investment opportunities. An economic analysis was conducted, but in the interest of preserving the scope and readability of the current study, it will be presented in a separate article (Manrique Delgado, Cao, Hasan, & Sirén, 2017).

This study focused on operational balances: the performance of the system is assessed through the electricity and heat exchanges with the hybrid grids. The energy, exergy, primary energy and emissions incurred during production, transportation or decommission/recycling of the system components have not been counted. This is in line with the requirements established in the NBCF and in the regulations of most European Union member states (D’Agostino, 2015). The results presented here could thus be useful as part of life-cycle assessments that would allow one to find sustainable energy solutions which consider all the stages throughout the lifetime of the system, but such assessments are beyond the scope of this study.

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**Notes**


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