Lifecycle cost and CO_2 emissions of residential heat and electricity prosumers in Finland and the Netherlands

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Abstract

The complexity of finding solutions to reach energy sustainability in the built environment poses a significant challenge. Therefore, there is interest in adequate management of the generation, conversion, storage, use and exchange of heat and electricity. The novelty of this study exists in presenting and comparing multiobjective optimizations for operational CO_2 emissions and lifecycle costs (LCC) of heat and electricity prosumers in the Netherlands and Finland, with and without net-metering. The premise relies on using surplus electricity to drive heat pumps for heat export instead of exporting surplus electricity. In the Netherlands, the calculated cost optimal solutions consist of using surplus electricity to drive an air source heat pump and export heat, with CO_2 emissions and ΔLCC of -41.1 $kgCO_2eq/(m^2\ a)$ and €-69.7/m^2 (22% lower), respectively. In Finland, the heat export strategy allows a ΔLCC of €-24.5/m^2 (8% lower), with CO_2 emissions reduced by -32.5 $kgCO_2eq/(m^2\ a)$. Without net-metering, the ΔLCC of the energy system rises to €-4/m^2 in the Netherlands; with net metering, the ΔLCC lowers to €-65.6/m^2 in Finland. The results indicate the potential for significant economic and emission reductions in heat and electricity prosumers.

Keywords: CO_2 emissions, LCC, heat and electricity prosumers, multiobjective optimization, renewable energy systems

Abbreviations

ASHP	Air source heat pump
DH	District heating
DHW	Domestic hot water
FH	Floor heating
GSHP	Ground source heat pump
HWST	Hot water storage tank
LCC	Lifecycle cost
NG	Natural gas
NPV	Net present value
NSGA-II	Non-dominated Sorting Genetic Algorithm II
NZEB	Net-zero energy building
O&M	Operation and maintenance
PE	Primary energy
PV	Photovoltaic
ST	Solar thermal
VAT	Value added tax
WT	Wind turbine
WP	Wood pellet

Symbols

A_{net}	Net conditioned area
A_{salv}	Salvage value
C	Expense
$CO_{2,eq}$	Equivalent CO_2 emissions
exp	Export
E	Energy
El	Electricity
F_1, F_2	Objective functions
F	Fuel
f_{CO2}	Specific emissions factor
$\mathrm{I}_{\mathrm{ini}}$	Initial investment
imp	Import
net	Net
$single$	Single
th	Thermal
Q	Heat
X	Exergy
x	Continuous design variable
y	Discrete design variable

1. Introduction

Through the Energy Performance of Building Directive (EPBD), all Member States of the European Union agreed to find and implement solutions to reach energy sustainability in the built environment [1]. This has sparked a vast amount of discussion and research in the countries involved, as each of them has its own socio-economical, cultural and environmental context, and thus each of them needs to find its own most suitable solution(s). This is seen in the varying building energy standards or references defined by each country, such as the Energy Saving Ordinance in Germany [2], the Nearly Energy Neutral Buildings (BENG) in the Netherlands [3], the French Thermal Regulation [4] and the National Building Code of Finland [5].

A topic that faces a high level of complexity is the interaction between the different forms of energy generated onsite and the energy demand of the building, which in turn influence the unidirectional and bidirectional exchanges between the building and the grid(s) [6]. Georges et al. [7] investigated the potential to improve the balance between onsite generation and demand. They found that load management and optimal sizing of photovoltaics (PV) systems enhanced load matching, cost savings and CO_2 emission reductions. Brange et al. [8] studied heat prosumers in Sweden and showed their potential to contribute significant amounts of heat to district heating grids, *heat prosumers* being buildings that generate a surplus of heat and export it beyond the system boundaries. Salom et al. [6] discuss indicators that aim to measure the interaction between generation,demand and grid, such as *load matching* or *grid interaction*. The authors highlight on the need to identify appropriate values for each of these indicators based on the type of building, the climate, and the energy type. Even though a net-zero energy building is commonly thought to be a building where the annual electricity consumption is equal to its annual electricity generation [9], buildings hardly rely on only one form of energy. Thus, Cao et al. [10, 11] identified the need for differentiating between electricity, heating and cooling, and developed and tested separate indicators for each. Their study shows the complexity of evaluating the performance of a system that includes energy grid connections, generation and storage components for different forms of energy. Moreover, in the definition of the 4th Generation District Heating, Lund et al. [12] contemplate smart interaction between the grid and the fluctuating energy sources, such as PV systems or wind power, and they warn that grid interaction with low-energy buildings is a major challenge since low-temperature sources and heat recycling might be required. Therefore, there is interest in adequate management of the generation, conversion, storage, use and exchange of various forms of energy in the built environment; failing to do so might leave the optimal solutions out of reach.

The complexity of this problem poses a significant challenge to the scientific community across Europe, since building topology, insulation levels, climate, energy supply and demand, prices, regulatory frameworks, and several other conditions must be addressed to evaluate the building performance. Single or multiobjective optimization can assist in this endeavor since it allows identifying optimal solutions when several variables are present. Multiobjective optimization enabled Mohamed et al. [13] to evaluate system configurations for small-scale multigeneration technologies in zero-energy buildings. The authors identified the optimal solutions in terms of cost and environmental benefits, as well as the effect of including PV panels in the system. The mixed integer linear programming approach by Harb et al. [14] showed that the optimal design and operation strategy of energy systems depends on the type of residential building. In their study, they found that boilers in combination with PV are preferable for single-family houses, while combined heat and power (CHP) and local heating networks are preferable for larger buildings and neighborhoods, respectively. Hamdy et al. [15] conducted a multi-stage optimization process to find the optimal combinations of building envelope and heat recovery options, and the corresponding optimal heating/cooling systems. Through this process, the authors found that fulfilling and surpassing the current energy standards in Finland can be achieved in a cost-optimal way, yet incentives are required get close to the net-zero energy level. While these are only a few examples of optimization studies on energy system design and/or management in the built environment, they illustrate the level of problem complexity that this method can handle and the quality of the information it can provide.

The reported literature gives an insight into the applicability of optimization in the study of the built environment, and into the challenge of optimal design and management of onsite energy systems. Thus, it is apparent that optimization can allow finding the energy solutions in buildings that deliver the best performance. Further, investigating heat and electricity, as opposed to simply *energy*, presents alternatives to how buildings can manage their onsite generation, and how they can exchange energy with its surroundings. As a result, multiobjective optimization of onsite heat and electricity systems in the buildings arises as an opportunity to come closer to sustainability in the built environment. This was investigated by Manrique Delgado et al. [17], where optimized energy systems for heat and electricity prosumers in Finland were presented. The study focuses on the environmental, economic and exergetic performance of a residential building with several energy configurations. Among them, an option to use a ground source heat pump (GSHP) to convert surplus electricity into heat for further export was presented and compared to other traditional heat supply options such as CHP and district heating. The results show that the heat export strategy can lead to optimal solutions concerning operational CO_2 emissions and lifecycle costs, yet the most cost-optimal solution is reached with a more conventional GSHP system without heat export capability. Overall, the results indicate potential and encourage further investigation of heat and electricity prosumers, particularly regarding their performances under various economical, climatic and energetic contexts.

The current study investigates the developed methodology [17] for its suitability in different conditions (the Netherlands) in order to evaluate the generic nature of the methodology. For this purpose, multiobjective optimizations for operational CO_2 emissions and lifecycle costs (LCC) of heat and electricity prosumers in the Netherlands and Finland. It relies on using surplus electricity to drive heat pumps with the purpose of exporting heat, instead of exporting the surplus electricity. While this aspect has been presented and investigated previously [17, 18, 19], the topic remains far from exhausted. The novelty of this article relies on four cornerstones. First, it presents the economic and emissions performance of heat and electricity prosumers in the Netherlands and describes the optimal energy system configurations. Second, the study presents the similarities, contrasts and transferable conclusions between prosumers in Netherlands and Finland. This provides an insight into the performance of the energy systems in two different contexts where climate, building typology, economic parameters, and energy practices are different. Third, the presence and capacity of the generation and storage components along the optimal fronts is studied in detail, and guidance on how to prioritize investments is given. Fourth, the article investigates the consequences for heat and electricity prosumers, and for regular prosumers, of a possible phase-out of net-metering in the Netherlands—which could lead to a poorer economic performance—and whether investments on energy components should be prioritized differently. Additionally, this study serves to reassert the potential of the heat export method by investigating its results under circumstances different from those in previous articles.

2. Description of the Dutch and Finnish contexts

This section presents the main characteristics of the Dutch and Finnish cases. The aim of the study is to address typical single-family households in the Netherlands and Finland adhering to the respective regulations. Further, cases with and without net-metering are studied for both countries, with the aim to test the system performance under current and hypothetical conditions. For instance, while district heating systems are not very common in the Netherlands, they are being encouraged [3]. In addition, a subcase is presented where CO_2 and initial investment are optimized. For detailed data, such as initial investments, O&M expenses and connection costs, please refer to Appendix A.

2.1. Buildings

The selected buildings adhere to strict building regulation frameworks in the Netherlands and Finland; Table 1 shows several of their features. In the Netherlands, the building is a semi-detached terraced house, which is a typical Dutch residential house [21, 3], representing about 40% of Dutch households [22]. The building is based on the BENG (Nearly Zero Energy Building) reference building by the Netherlands Enterprise Agency (RVO) [3]. A detailed description and the layout of the three-storey building can be found in Kotireddy et al. [23]. The Finnish building is based on Villa ISOVER, a pilot project between the two companies ISOVER and Fortum on the incorporation of onsite generation components in a highlyinsulated single-family house. It is a detached two-storey building that adheres to and exceeds the regulations in Decree D3 of the National Building Code of Finland [5]. Further information about Villa ISOVER is available in [25, 26]. The simulation model for Villa ISOVER was calibrated and validated based on measured data from the building [18], with errors between the simulated and measured data of roughly 5% and 3% for energy demand and supply, respectively.

Table 1 – *Features of the buildings modelled for the Dutch and Finnish cases.*

2.2. Heat supply options

The studied Dutch heat supply systems consist of natural gas (NG) boilers—around 97% of residential houses in the Netherlands use gas-based boilers [27]—and air source heat pumps (ASHP) with and without heat export, whereas in Finland, the options are wood pellet (WP) boilers, and GSHP with and without export. Boilers cannot be operated with electricity, and thus offer no potential to convert surplus electricity into heat for further export. Heat pumps offer this possibility, and they are also common in both countries. Also, they produce several units of heat per unit of consumed electricity, and therefore they are attractive for the purpose of this study. Currently, due to local weather and ground conditions, ASHPs are more preferred in Netherlands [28], while GSHPs have been suggested as optimal solutions for single-family buildings in Finland [29]. All heat supply options are assumed to include a hot water storage tank (HWST) with a capacity of 750 liters

2.3. Economic aspects

The energy prices depend on the energy carrier, the case study and the country. The Netherlands has implemented support mechanisms for residential onsite generation technologies, such as net-metering and tax deductions. Net-metering allow users to import and export energy from and to the grid whenever required, ideally at the same price. There is a limitation in the Netherlands: if annual export exceeds the annual import, the surplus is paid at a lower rate. It is uncertain whether this support scheme will continue beyond 2020 [30, 31]. Finland has not implemented net-metering; the import price includes the spot market price in NordPool [32] plus an energy tax and a transmission fee, and the export price consists only of the spot market price minus a commission fee. Table 2 shows the electricity import and export prices and feed-in tariff rates of the net-metering scenarios for both countries. The prices without net-metering in the Netherlands and the prices with net-metering in Finland are assumptions based on the current price scheme in each country. For the Netherlands, in the case of net-metering termination, the lower feed-in tariff rates of the net-metering scenario are used for exported electricity irrespective of the annual energy balance. In Finland, the import and export electricity prices with net-metering are assumed to be equal to the respective average prices in 2015.

Regarding the price of exported heat, assumptions have been made for both countries, as such strategy has been implemented to a very limited extent. An example is the open district heating grid in Stockholm, one of the few existing grids that supports the heat export strategy [35]. In the Netherlands, the price is assumed to be 40% of the operational energy cost of heat from an NG boiler. That is, the price of NG divided by the boiler efficiency. In Finland, the price is assumed to be 40% of the price of heat from a district heating grid; these price assumptions are comparable with the prices in the open district heating grid in Stockholm. The heat export prices in the Netherlands and Finland at the beginning of the simulation amount to €0.034/kWh and €0.038/kWh, respectively.

Table 2 – *The electricity import and export prices with and without net-metering in the Netherlands and Finland* [33, 34, 32] *in euro cents per kWh. The annual balance is positive if the exported electricity is larger than the imported electricity, and vice versa.*

The electricity price escalation rates in the Netherlands and Finland are 1% and 4%, respectively, calculated based on the nominal historical prices as shown in Figure 1. These prices correspond to the average values for each year, unadjusted for inflation or else. The price of NG in the Netherlands and the price of wood pellets (WP) in Finland remain constant throughout the year, starting at €0.077/kWh and €0.058/kWh, respectively, with price escalation rates of 1% and 3.5%, respectively. The interest rate is set at 3% in both countries.

Further support schemes are available in both countries. In the Netherlands, the VAT on the acquisition of photovoltaic (PV) systems is returned. In Finland, a 45% tax deduction can be applied for on the installation costs of PV and wind turbine (WT) systems [38].

Figure 1 – *The nominal historical prices and price trends for various energy carriers for detached houses in the Netherlands* [36] *and Finland* [34, 37]. *(El.: electricity; NG: natural gas; WP: wood pellets; NL: Netherlands; FI: Finland)*

2.4. Emission factors

The specific emission factors in the Netherlands and Finland for the energy carriers are shown in Table 3. Exported energy is assumed to replace energy production by the utilities, and thus there is no distinction between factors for the import and export of electricity. It is also assumed that the generation from PV, WT and solar thermal (ST) collectors has no operational emissions. Regarding heat export, in the Netherlands, it is assumed to have an emission factor of 220.3 $kgCO_2eq/MWh$ (replacing heat supplied by an NG boiler). In Finland, heat export is assumed to replace import from a district heating grid, with an emission factor of 245 $kgCO_2eq/MWh$ [39].

Table 3 – *The specific emission factors f_{CO2} in kgCO₂eq/MWh for the energy carriers in the Netherlands and Finland used in this study.*

3. Research method

In this section, the definition of the optimization problem and the approached method are presented. This includes the optimization problem itself, the mathematical expressions used to calculate the objective functions, the design variables, the simulation environment, and the multiobjective optimization tool and algorithm.

3.1. The optimization problem

The optimization problem in each case study is defined as

$$Min\,\{F_1(\boldsymbol{x},\boldsymbol{y}), F_2(\boldsymbol{x},\boldsymbol{y})\} \tag{1}$$

where

$$\boldsymbol{x} = \left(x_{PV}, x_{WT}, x_{ST}, x_{Battery}\right)^T and\ \boldsymbol{y} = \left(y_{STConn}, y_{HeatSys}\right)^T \tag{2}$$

where F_1 and F_2 are the objective functions, vector $\boldsymbol{x}$ contains the continuous design variables and vector $\boldsymbol{y}$ contains the discrete design variables. The problems are unconstrained. Each decision variable (for a detailed description, see Table 4 and Table 5) represents (i) the installed capacity of the system components, $x_{PV}, x_{WT}, x_{ST}, x_{Battery}$, (ii) whether the ST collectors can export heat or not, y_{STConn}, or (iii) the main heat supply component, $y_{HeatSys}$.

3.2. Objective functions

The objective functions in this study are the annual operational equivalent CO_2 emissions of the system, and its LCC. For simplicity, the annual operational equivalent CO_2 emissions are henceforth referred to simply as CO_2 emissions.

The CO_2 emissions $CO_{2,eq}$ in kgCO₂eq/(m² a) are calculated as

$$CO_{2,eq} = \frac{\left(El_{imp} - El_{exp}\right) \cdot f_{CO2,El} + E_{NG} \cdot f_{CO2,NG} + E_{WP} \cdot f_{CO2,WP} - Q_{exp} \cdot f_{CO2,off}}{A_{net}}, \tag{3}$$

where El_{imp} and El_{exp} are the annual electricity import and export respectively, E_{NG} and E_{WP} are the NG and WP energy demand respectively, $Q_{exp}$is the exported heat and $f_{CO2,EL}$, $f_{CO2,NG}$, and $f_{CO2,WP}$ are the specific emissions factors for electricity, NG and WP respectively. $f_{CO2,off}$ is the specific emissions factor for emissions reduction by heat export, which is calculated independently for each case study.

The LCC of the system is calculated as

$$LCC = I_{ini} + C_{O\&M} + C_{single} + C_E + A_{salv} \, , \tag{4}$$

where the net present value (NPV) of operational cash flows and salvage values are considered. I_{ini} represents the initial investment including component prices, installation costs and connection costs, $C_{O\&M}$ represents the discounted operation and maintenance (O&M) costs of the system components, C_{single} represents the discounted single entry expenses that occur every few years, such as component replacements, C_E represents the discounted cash flow due to energy and/or fuel purchases and sales along with any service fees that may apply, and A_{salv} represents the discounted salvage value of the components that can be sold at the end of the lifetime considered in this study. To account for the price development of the energy carriers, the NPV calculation of C_E uses a real interest rate that reflects price escalation rates. To focus on the influence of the design variables, and for ease of interpretation, a differential lifecycle cost ΔLCC is used, which is the difference between each case—with different values for the design variables—and the reference case—which represents the most common energy supply method in each country; the latter is defined independently for each case study.

3.3. Design variables

The design variables in this study represent the options for onsite heat and electricity generation, storage and exchange. They address the installed capacity of PV, WT and ST collectors, the battery size, ability of the ST collectors to export heat, and the main heat supply component. The maximum size of the PV system has been defined based on the rooftop area of the reference buildings; a comparable size for the WT system has been defined. The lower limit for the battery state of charge is 30%. The particular characteristics of the variables are shown in Table 4 and Table 5. One multiobjective optimization process is performed for each tag value of variable $y_{HeatSys}$; this allows finding the optimal results for each heating system and prevents loss of information, thus overall offering a better basis for the analysis and comparison of the results. Moreover, since the tag values represent different components rather than more typical increasing or decreasing values, running a single optimization for all tags of $y_{HeatSys}$ is detrimental to the quality of the results.

Table 4 – *Design variables in the optimization.*

Table 5 – *Features of the design variable for the main heat supply component* $\boldsymbol{y_{HeatSys}}$.

The installed capacity of GSHP and ASHP depends on the export capability: if heat export is not allowed the installed capacity is 6 kW, whereas if heat export is allowed the installed capacity is 8 kW (see Table 5). This approach is taken based on Manrique Delgado et al. [17], where the results indicated that a higher installed capacity is preferred when heat export is allowed.

In order to ensure that heat export by the ST collectors, GSHP or ASHP has no negative impact on the energy supply of the building, the following rules have been implemented:

- The ST system can export heat only if the temperature in the bottom of the HWST is 60 °C or higher.
- The GSHP and ASHP can export heat only if the electricity demand of the building is covered (i.e. the GSHP or ASHP are operated with surplus electricity), the heat demand of the building is covered (satisfying the heat demand of the building has priority over heat export), and the battery is fully charged.

3.4. Simulation and multiobjective optimization

The building and energy systems have been modeled in TRNSYS 17, a simulation environment for transient systems [43]. The simulation corresponds to one year of operation, with a time-step of 0.25 hours. The model includes a network comprising the energy generation, storage and demand components, the connections between them, the weather processors and the required control systems. Moreover, the calculation of the objective functions takes place within the model, not during post-process. The weather input for the Netherlands is based on the typical climate reference year NEN 5060:2008, which is based on the average months of 20 years of historical data [46]. The weather input for Finland is based on the test reference year TRY2012 [24].

The optimization process was performed in MOBO, a tool for multiobjective building performance optimization [47, 48]. The optimization algorithm Pareto archive NSGA-II has been chosen from the algorithm library available in MOBO. NSGA-II stands for *Nondominated Sorting Genetic Algorithm II*, an evolutionary algorithm developed by Deb et al. [49]. As recommended by Alajmi et al. [50], the population size is small, the crossover probability is high and the mutation rate is low, with values of 8, 100% and 20%, respectively. To find out the number of generations needed to find the optimal (or near-optimal) solutions, a pre-optimization process with 100 generations was conducted and the number of generations after which the Pareto front no longer showed a significant improvement was found. Further information about this procedure is given in [17]. The number of generations was set at 45, for a total of 360 simulations per case study. Different values in the variables, particularly in variable $y_{HeatSys}$, lead to different simulation times and subsequently to different optimization times. A defined optimization time can thus not be given, only an approximate of roughly 1.5 to 2 days of calculation time per optimization, for a total of 20 to 22 days for the entire set of optimizations. A flow diagram of the simulation and optimization process is shown in Figure 2. Both the TRNSYS model and the optimization have been implemented with standard and/or available components and tools (e.g. Type94b for PV, Type1a for ST). Therefore, the method used in this study can be replicated through the use of similar dynamic simulation environments and optimization tools.

Figure 2 – The flow diagram of the simulation and optimization process.

4. Results & discussion

In this section, the results of the multiobjective optimizations are presented and discussed. First, those related to the Netherlands, followed by those related to Finland; the section closes with a comparison between the two countries.

4.1. The Netherlands

The Pareto fronts for the three heating systems for the Dutch case with and without net-metering are shown in Figure 3. The reference case consists of a system with an NG boiler, a connection to the electricity grid, and no other heat or electricity generation components. The results show that ASHPs offer the optimal solutions under both net-metering options, provided that there is a provision for heat export. This is attributed to the higher monetary income from exported heat, of €0.13, than from exported electricity (assuming an annual surplus), of €0.07.In case of net-metering, NG boilers have a lower ΔLCC compared to ASHPs without heat export due to the lower investment cost of boilers. However, as more onsite generation capacity is available, the optimal option between an NG boiler and an ASHP without heat export depends on net-metering: if net-metering is available, ASHP is preferred in most of the front, whereas if net-metering is not available, ASHP and NG boiler compete closely along the front. This is because an ASHP benefits more from net-metering—an electricity oriented support scheme—than an NG boiler.

An ASHP with heat export has the lowest ΔLCC with net-metering compared to other heating systems: €-69.70/m^2 with CO_2 emissions of -41.1 kgCO_2eq/(m^2 a), yet increases to €-4.0/m^2 without net-metering, with no significant change in CO_2 emissions. This is attributed to heat export, which allows reduction of CO_2 emissions irrespective of net-metering. In cases of no heat export, the ΔLCC of an ASHP increases to €-17.5/m^2, and CO_2 emissions increase to -26.6 kgCO_2eq/(m^2 a) with net-metering, and to €71.1/m^2 and CO_2 emissions of -15.2 kgCO_2eq/(m^2 a) without net-metering. It is worth noting that the LCC is higher in cases of no net-metering due to the lower income from exported electricity. Overall, an ASHP with heat export is the optimal heating system with and without net metering. A natural gas boiler should be preferred if the ΔLCC is prioritized and heat export is not allowed. A detailed investigation on the cost-optimal systems is shown in Appendix B.

It can be observed from Figure 4 that the capacities for PV have similar trends for the three heating systems with and without net-metering. The same observations can be made for WTs. Scattered capacities are observed for ST and battery for both net metering options.

Figure 3 – *The Pareto fronts for ASHP with and without heat export, and for boiler. The fronts are shown for the Dutch case with (top) and without (bottom) net-metering.*

The difference in PV system capacities on the Pareto fronts with and without net-metering is not significant, the only differences being the optimal capacity of a PV system for an ASHP with no heat export and for a boiler in case of no net-metering. Cost optimality is lessened if there is no net-metering, as the excess exported electricity yields lower benefits at the same investments costs. If heat export is allowed, higher capacities of PV system yield optimal investment options as excess electricity generated by a PV system can be utilized by the ASHP to generate heat. Overall, the optimal capacity of a PV system for the three heating systems is between 9 to 10 kW, with a few solutions between 8 to 9 kW. An investigation on larger installed capacities of PV can be found in Appendix B.

In contrast to the optimal capacities of PV systems, the trends for the optimal capacity of WTs cover the entire range for the three heating systems with and without net-metering. There is no observable influence of availability of net-metering on the overall investment strategy in WTs. WTs offer better energy matching than PV systems due to their more evenly distributed energy generation throughout the days and the seasons; this allows a higher rate of self-consumption, which reduces the export of surplus electricity and thus the effect of net-metering.

Even though there is no definite trend for a ST collector area on the fronts, it can be observed from Figure 4 that higher capacities of ST systems dominate the Pareto front of ASHPs with and without export when net-metering is available, and lower capacities otherwise. However, for the boiler, the capacities of ST systems remain mostly unchanged on an average of 7 m^2e. This indicates that heat generated by a ST system can enhance the performance of ASHPs by (a) reducing the need to operate the ASHP to cover heat demand by the building, and by (b) allowing the ASHP to export more heat. This second point is because PV and ST generation are dependent on solar radiation; when the sun is shining, the ASHP, driven by surplus electricity, can focus more on heat export since the ST collectors assist to cover the building heat demand.

Similar to the ST capacities on the fronts, scattered values for battery size are observed for the three heating systems, yet the effect of net-metering is clearly visible: the average battery capacities for ASHP with heat export are 1.8 kWh with net-metering and 3.6 kWh without net-metering. This is attributed to the grid acting as virtual storage in case of net-metering. The installed battery capacities for an ASHP without heat export and an NG boiler are similar for both net-metering options, with scattered values across the whole front. While this could seem counter intuitive, it is an indication that the battery size has little influence on the results, and the optimization algorithm prioritizes exploring other variables.

Figure 4 – *Installed capacity of onsite generation and storage components on the optimal fronts for an ASHP with and without heat export, and for a natural gas boiler. Capacities are shown for the Dutch case with (left) and without (right) net-metering.*

4.2. Finland

Figure 5 shows the Pareto fronts for the three main heat supply components, for the Finnish cases with and without net-metering. The reference case consists of a system that covers its heating and electricity demands through imports from the district heating and electricity grids. The results of the multiobjective optimization show that GSHPs offer the optimal solutions for LCCs and CO_2 emissions. As for comparing between GSHPs with and without heat export, the results without net-metering show that the lowest ΔLCC, €-46.5/m^2, is reached when the GSHP cannot export heat. For comparison, the lowest ΔLCC for a GSHP with export is €-24.5/m^2. Yet, while there is an increase in the LCC, the system with heat export allows a significant reduction of 20.2 $kgCO_2eq/(m^2\ a)$, offering a net compensation of CO_2 emissions. If net-metering is available, the lowest LCC for GSHPs without and with heat export drop to €-84.2/m^2 and €-65.6/m^2, respectively. Otherwise, there are no major differences between the cases with and without net-metering (see Figure 5).

As in the Dutch case, the dominance of heat pumps on the Pareto front relies on the COP of this component. Let us assume there is 1 kWh of surplus electricity generated by the PV system. If it were directly exported to the Finnish grid, it would compensate 0.173 $kgCO_2eq$, and the income from its sale would be roughly €0.03. Yet, if it were converted to heat and exported to the heating grid, it would compensate 0.857 $kgCO_2eq$, and the income from its sale would be roughly €0.13. That is, by converting 1 kWh to heat for export, the system compensates 4.9 times more emissions and brings 4.3 times more income. Regarding the LCC difference between the GSHP with and without heat export, the heat export option dominates the top part of the front due to the higher monetary income from exported heat, while the electricity export option dominates the bottom part due to its lower initial investment. Moreover, the presence on the optimal front of GSHPs with export indicates that the income from heat export can justify the additional spending on borehole depth and connection costs if onsite electricity generation is available and sizable.

Figure 5 – *The Pareto fronts for GSHPs with and without heat export, and for boilers. The fronts are shown for the Finnish case without (top) and with (bottom) net-metering.*

It can be observed from Figure 6 that with net-metering the optimal results have at least 6-kW PV capacity, regardless of the main heat supply component, whereas without net metering several systems with lower PV capacity are present on the optimal fronts of GSHPs without export and boilers. The lower PV capacities when net-metering is not available reinforce the notion that net-metering has a positive effect on the economic performance of PV systems. An investigation on larger installed capacities of PV can be found in Appendix B. Regarding batteries, Figure 6 shows that there is no clear pattern when the system includes a boiler or a GSHP without heat export. However, if a GSHP with export is present, the battery size should be below 3 kWh.

Figure 6 – *Installed capacity of onsite generation and storage components on the optimal fronts for GSHPs with and without heat export, and for boilers. Capacities are shown for the Finnish case with (left) and without (right) net-metering.*

These results indicate that investments in onsite electricity generation components should be first directed to the PV system, followed by WTs. The results are not as conclusive regarding whether investments in ST collectors or WTs are preferred, since they seem to be related to the main heat supply component. For GSHPs without heat export and boilers, the investments in ST collectors along the Pareto front are concentrated mostly between 8 and 10 m^2, whereas for GSHPs with export the investments are concentrated mostly between 0 and 2 m^2. Particularly, when a GSHP is allowed to export investing in WTs is more attractive than investing in ST collectors, since more surplus electricity by WTs (to generate and export heat) brings higher income than more surplus heat by the ST collectors. In contrast, when a GSHP is not allowed to export, WTs and ST collectors compete more closely, and thus investment in both is significant.

The availability of net-metering is shown to have limited effects on the behaviour of the optimal fronts and component investments. It is remarkable that batteries do not show a defined trend when a boiler or GSHP without export are present. This could be due to their relatively scarce effect on the results, since batteries have relatively lower prices and lower overall influence on the system compared to PV, WT and ST collectors. Yet, if a GSHP with export is present, the battery size should be kept low so as to promote heat export, which explains the distribution seen in Figure 6.

4.3. Similarities and contrasts

A significant difference is that the environmental attractiveness of converting surplus electricity into heat for export is lower in the Netherlands than it is in Finland, due to the high emission factor of electricity in the Netherlands. For instance, if 1 kWh of surplus electricity is exported to the grid, it compensates 0.540

$kgCO_2eq$, while if it were converted to heat and exported to replace heat from an NG boiler, it would compensate 0.969 $kgCO_2eq$. Thus, converting 1 kWh to heat the system compensates roughly 1.8 times more emissions. While this is attractive, in Finland the ratio is considerably higher, at 4.9.

Moreover, the climatic differences between the Netherlands and Finland have notable impacts on onsite energy generation. The higher solar radiation in the Netherlands means a higher output per unit of installed capacity than in Finland. As an example, a 1-kW PV system delivers 1,111 kWh/a of electricity in the Netherlands but only 907 kWh/a in Finland. This, in combination with the different export price schemes, could translate into an income of €77.8 in the Netherlands and €29.0 in Finland, assuming all the generation is exported as surplus, or into annual savings of €222.0 in the Netherlands and €139.0 in Finland, assuming all the generation is used onsite.

4.3.1. Heating systems

The results of the multiobjective optimizations of heating systems for the Dutch case (Figure 3) and the Finnish case (Figure 5) show that heat pumps offer the optimal solutions for LCCs and CO_2 emissions with and without net-metering. However, if heat export is not available, the NG boiler has the lowest LCC in the Dutch case regardless of whether net-metering is available or not. This is attributed to the lower initial investment of NG boilers in the Netherlands. Notably, it is found that ASHPs and GSHPs with heat export result in the lowest CO_2 emissions for both net-metering options.

A reason for the differences between the Dutch and Finnish contexts is the type of heat pumps. In the Netherlands, ASHPs are more common, as winters are milder and the component can offer a satisfactory performance throughout the year. This is not the case in Finland, where outdoor temperatures during winter are lower and ASHP performance is drastically diminished. GSHPs are more common in Finland, as the ground temperature is not as low as the ambient air temperature, which subsequently helps the COP to remain acceptable.

4.3.2. Fluctuating generation components

High capacities of PV systems—between 9 to 10 kW for the Dutch case and between 6 to 10 kW for the Finnish case—are found to be optimal irrespective of heating system type in the case of net-metering. However, in the case of no net-metering, this optimal capacity lower limit reduces for ASHPs with no heat export to 8 kW in the Dutch case. This reduction is even greater in the Finnish case—it is close to zero for GSHPs with no heat export. The optimal capacity of a WT system varies from 0 to 10 kW for both the Dutch and Finnish cases for all heating systems and net-metering options. Overall, the behaviour of investments in WT systems shows no significant differences between countries.

ST collectors show more distinct differences between the Dutch and Finnish cases. However, in the Finnish case, the investments in ST collectors are rather polarized They tend to be low for GSHPs with export, yet high for the two other heat supply systems, whereas in the Dutch case, the investments on ST collectors are quite scattered and thus less conclusive.

4.3.3. Electricity storage component

The availability of net-metering is shown to have limited effect on the behaviour of the investments on electricity storage components in the Dutch and the Finnish cases, with average installed capacities of 3.6 and 2.8 kWh, respectively. Thus, this component does not seem to have a strong impact on the system performance of the studied cases, with the only remarkable effect of net-metering being shown in ASHP with heat export in Netherlands.

4.4. Initial investment subcase

A supplementary set of multiobjective optimizations was conducted for both countries: CO_2 emissions and initial investment. This subcase allows studying the heat export strategy from the perspective of a contractor, who pays the initial cost yet does not benefit from savings. The results are shown in Figure 7. Net-metering has no effect in these optimizations; therefore, only one set of results is presented.

Boilers provide optimal solutions with low initial investment in both countries. This is a consequence of the lower price of boilers compared to ASHP and GSHP, and of the lower specific emissions factor of NG and WP compared to the specific emissions factors of electricity in the Netherlands and Finland, respectively. These factors also explain the steep decrease in the lower part of the fronts: as investment in onsite electricity generation components increases, the CO_2 emissions caused by electricity imports decrease sharply. As the initial investment increases, surplus electricity from onsite generation components becomes available for generating and exporting heat, thus allowing heat pumps with heat export capability to become optimal solutions in both countries.

The Pareto fronts in the Finnish case shows that, except for systems with little to no investment on onsite generation components, the results for GSHP with heat export dominate those for GSHP without export. This is a consequence of the COP and of higher specific emissions factor of DH compared to that of electricity: not only can more units of heat than of electricity be exported, but each unit offsets of heat offsets more CO_2 emissions. In contrast, the high specific emissions factor of electricity in the Netherlands causes both options of ASHP to compete closely in the lower portion of the fronts: only when the size of PV system reaches roughly 7 kW does ASHP with heat export become the identifiable optimal solution.

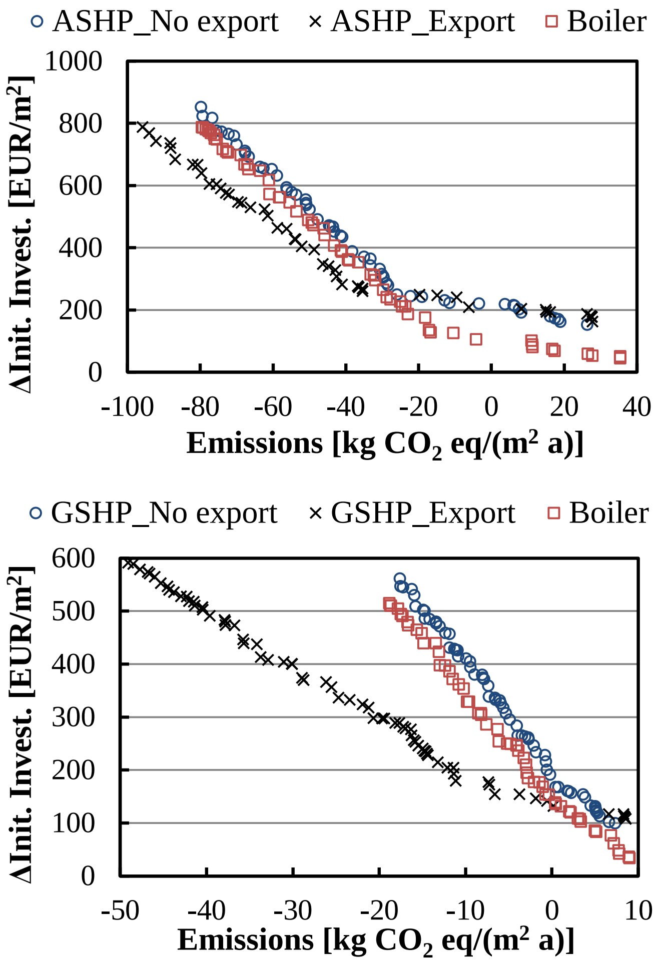

Figure 7 – *The Pareto fronts of the multiobjective optimization for CO_2 emissions and initial investment. The fronts are shown for the Dutch case (top) and the Finnish case (bottom).*

The results of this subcase show conflictive preferences at low investments: the optimal solutions for a contractor require a boiler while the optimal solutions for an end user require a heat pump. In an ideal situation, an informed end user would cover the higher initial investments knowing that the savings will exceed the costs, yet other users might prioritize low initial costs. Moreover, a contractor might prefer solutions with a low initial cost as they can be afforded by a larger portion of the population. Therefore, understanding of the immediate and long-term economical advantages of the system is necessary to ensure that the energy system is optimal—or close to optimal—for both parties.

4.5. Uncertainty analysis

An uncertainty analysis was conducted to address the influence of changes in the economic context. Two economic parameters were investigated: the energy price escalation rates and the heat export price. The energy price escalation rates are set at 0% and 2%, while the heat export price are set as 30% and 50%. An uncertainty analysis for the Finnish case is not presented in this study, as it has been addressed by Manrique Delgado et al. [17] for a similar optimization problem.

Figure 8 shows non-dominated fronts for CO_2 emissions and the ΔLCC for the optimizations with 0%, 1% and 2% energy price escalation rates. The results for all systems show similar behaviour: higher escalation rates lead to lower ΔLCC, because higher escalation rates mean higher income from energy export in the future. The difference in LCC caused by the escalation rates is more pronounced at high values of ΔLCC. This difference can be explained by the investments in onsite generation: as investments increase, energy export increase, and thus the energy price escalation rates have a stronger effect on the LCC. Regarding the investments in PV, WT, ST collectors and battery capacity, there are no remarkable differences compared to the optimization with the calculated energy price escalation rates.

Figure 9 shows the non-dominated fronts for ΔLCC and CO_2 emissions for the optimizations with a heat export price at 30%, 40% and 50% of the retail price. It can be seen that lower export prices lead to higher LCCs. This is a consequence of the income from heat export: the higher the export price, the higher the income. Further, it can be seen that at the top of the figure the difference between ΔLCCs can reach €119/m^2 for similar emission levels, whereas at the bottom it decreases to €36/m^2. The reason for this difference in ΔLCC is the amount of exported heat. The influence of the export price of heat increases along the front, simply because there is more heat to export. Regarding the investments in PV, WT, ST collectors and battery capacity, there are no remarkable differences compared to the optimization with 40% of the retail price.

Overall, the results of the uncertainty analysis show that the main findings discussed above remain valid under the tested conditions. That is, the LCCs of the systems investigated are influenced by the escalation rates and by the heat export prices, yet there is no notable change in the observation that ASHPs with heat export offer the lowest ΔLCCs and a significantly higher compensation of CO_2 emissions. Moreover, the observation that the optimal front for ASHPs with heat export dominates the optimal front for ASHPs without heat export remains valid. Regarding the investment in other components such as PV or WT systems, no significant changes were observed.

Figure 8 – *The non-dominated fronts for an ASHP without export (top), an ASHP with export (bottom left) and (bottom right), with calculated (1%), low (0%) and high (2%) energy price escalation rates.*

Figure 9 – *The non-dominated fronts for an ASHP with export at different heat export prices, shown as a percentage of the retail price, and for an ASHP without export and boiler.*

5. Conclusions

This study consists of multiobjective optimizations for CO_2 emissions and LCCs of residential-scale energy systems with onsite electricity and heat generation components. Moreover, two different energetic, economic and climatic contexts were explored: the Netherlands and Finland. The main outcomes of the study are as follows:

- Heat pumps represent the optimal main heat supply component in the Netherlands and Finland, and the PV system is the most attractive supplementary onsite generation component followed by WTs.
- The environmental attractiveness of converting surplus electricity into heat for export is lower in the Netherlands than in Finland due to the CO_2 emission factors.
- The calculated optimal investments in the PV system in the Netherlands start at 8 kW without net-metering and at 9 kW with net-metering, whereas in Finland, the calculated optimal investments in the PV system start at 6 and 0 kW, respectively. However, the maximum optimal PV capacity would likely require an area that exceeds the typical rooftop area of a single family building.
- Overall, investments in PV systems should be preferred over investments in WT systems, with no significant differences based on the country.
- Energy systems, where surplus electricity is used to drive an ASHP and export heat, leads to optimal solutions for CO_2 emissions and ΔLCCs in the Netherlands, with calculated values of -41.1 $kgCO_2eq/(m^2\ a)$ and €-69.7/m^2 for the cost-optimal solution.
- Net-metering allows reducing the calculated ΔLCC of the energy system by 65.7/m^2 in the Netherlands. The availability of net-metering does not affect the performance ranking of the studied heat and electricity systems, and no significant differences arise in the energy system configuration if net-metering is present or not.
- The results of the uncertainty analysis to energy price escalation rates and heat export prices in the Netherlands show that the performance ranking of the studied heat and electricity systems remain valid under the tested conditions.
- Energy systems consisting of a GSHP with and without the ability to export heat lead to optimal solutions for CO_2 emissions and ΔLCCs in Finland, with calculated values of 8.9 $kgCO_2eq/(m^2\ a)$ and €-46.50/m^2 for the cost-optimal solution. The Pareto front consists of systems including a GSHP with the ability to export surplus heat, except in its bottom part, which consists of systems without this ability.
- Net-metering allows reducing the calculated ΔLCC of the energy system by €41.0/m^2 in Finland. As in the Netherlands case, the availability of net-metering does not affect the performance ranking of the studied heat and electricity systems, and no significant differences arise in the energy system configuration if net-metering is present or not.

- Boilers are the optimal main heat supply components for systems with low initial investments, whereas heat pumps are optimal for systems with low LCC. This may create a conflict of interests between the investor and the end user.

The outcomes rely on the assumption that an unlimited amount of heat can be exported to the grid. While this might seem counterintuitive, particularly during summer when heating demand is low, the assumption is supported by the increasing interest in smart and efficient use of energy. Therefore, the exported heat could be used in district cooling – through thermal cooling [51] – and/or in other thermally activated technologies [52], seasonal storage, or to cover domestic hot water demand. Thus, as the energy systems continue to develop, heat export to district grids has potential to become a common practice.

The contexts explored in this study give valuable insight into the potential of prosumers in central and northern Europe, yet significant differences might arise in other geographical locations, indicating the need for separate case study assessments. Furthermore, the support schemes to promote renewable energy systems in single-family houses have a clear effect on the economic attractiveness of investing in such components. Finally, the variable ranges should be adapted for each particular case, so as to find the optimal energy system for the available conditions.

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Appendix A: Prices

Figure A shows the prices (including VAT) per installed capacity for several system components. PV prices in the Netherlands are calculated as 700+925**x*, where *x* represents the PV capacity in kW; the curve in the figure shows the price per installed capacity. All prices shown include installation costs, except for the ST collectors; for this component the installation costs are assumed to be equal to the price of the ST collectors. Battery prices are calculated as $192.09\ x^{0.717}$, where *x* represents the battery size in kWh. Borehole and piping prices are calculated as €33.45/m of borehole depth and €15.00/m^2 of gross building area, respectively. The borehole depth was calculated using Earth Energy Designer [53] based on the onsite electricity generation capacity. Table A shows the annual O&M costs for PV, WT and ST components. Table B shows the lifespan of the components that require replacement. Table C shows the initial investment and O&M costs for the main heat supply components, and Table D shows the references for the initial investment and O&M costs.

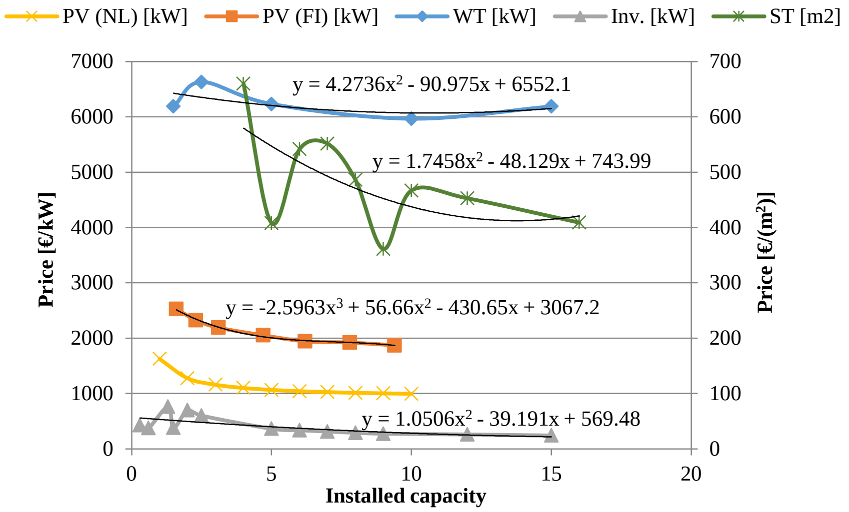

Figure A – Prices and price trends for system components.

Table A – Annual O&M costs as percentage of the initial investment for PV, WT and ST components.

Generation component	**Annual O&M**
PV	1%
WT	1.5%
ST	0.75%

Table B – Lifespan of system components that require replacement.

Component	Lifespan [years]
Inverter	12
Battery	10
ASHP/GSHP	20

Table C – Initial investment and O&M costs of the main heat supply components.

Heat supply component	Initial investment [€]	Annual O&M cost
GSHP – 6 kW	5300	1.5% of initial investment
GSHP – 8 kW	5500	1.5% of initial investment
ASHP – 6 kW	12,995	1.5% of initial investment
ASHP – 8 kW	13,545	1.5% of initial investment
Boiler – WP	3582	€139.2
Boiler – Gas	1099	€130.44

Table D – Sources for the initial investment and O&M costs of system components.

Component	Initial Investment		O&M	
	Source	URL	Source	URL
PV (NL)	Netherlands Enterprise Agency RVO, 2014	http://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/utiliteitsbouw/beheer-en-onderhoud/investeringskosten	National Renewable Energy Laboratory	nrel.gov/docs/fy15osti/63235.pdf
PV (FI)	Fortum	fortum.com		
WT	The Renewable Energy Hub UK	renewableenergyhub.co.uk	Wind Measurement International	windmeasurementinternational.com/wind-turbines/om-turbines.php
Inverter	Nettiosa	nettiosa.com	-	-
	Aurinko	aurinkosinoorit.fi		
	Finnwind	verkkokauppa.finnwind.fi		
ST	Ympäristoenergia	energiakauppa.com	National Renewable Energy Laboratory	nrel.gov/analysis/tech_cost_om_dg.html
	Sundial	sundial.fi		
	JTV-Energia	jtv-energia.fi		
Battery	Wholesale Solar	wholesalesolar.com/	-	-
Borehole and piping	Building Construction Cost Data 2013 [Talonrakennuksen kustannustieto 2013]	-	-	-
GSHP – 6 kW	Taloon	taloon.com/ds/hakutulokset?q=nibe+1145	Mohamed, Hamdy, Sirén	dx.doi.org/10.1016/j.apenergy.2015.04.096
GSHP – 8 kW				
ASHP – 6 kW	Mitsubishi Electric	Direct quote		
ASHP – 8 kW				
Boiler – WP	National Renewable Energy Laboratory	nrel.gov/analysis/tech_cost_dg.html	British Gas	britishgas.co.uk/home-services/home-cover/
Boiler – Gas	Warmgarant	https://www.warmgarant.nl/cv-ketel-kopen/uw-cv-ketel-samenstellen/intergas-hreco-24.aspx	Warmgarant	https://www.warmgarant.nl/cv-ketel-kopen/uw-cv-ketel-samenstellen/intergas-hreco-24.aspx

Appendix B: Complementary investigations

B.1: Cost-optimal systems verification

The optimization algorithm aims to cover most of the non-dominated front. Nevertheless, being a stochastic algorithm, it might not succeed in finding the two optimal extreme solutions at the two ends of the Pareto front. Since the minimum LCC point is the lower extreme point in the optimization search, therefore and to ensure that the ASHP with heat export offers the solutions with lowest LCCs in the study case, a supplementary set of simulations has been conducted. These optimizations use the exhaustive search algorithm in MOBO (Brute-force search) with discrete variables. The insights about the upper and lower limits and steps of the discrete variables are learned from the lowest-LCC results of the case study optimization for each main heat supply system in Figure 3. The results of these supplementary simulations are shown in Figure B.1, with a total of 469 simulations.

As can be seen in Figure B.1, the observation that ASHPs with heat export offer the lowest LCC is supported by the explorative simulations. Moreover, a lower LCC solution has been found with €-84.10/m^2 and CO_2 emissions of -38 $kgCO_2eq/(m^2\ a)$. These results support that the method allows the identification of the main heat supply components that offer the lowest LCCs, yet they also remind us that solutions found by stochastic optimization algorithms are near-optimal.

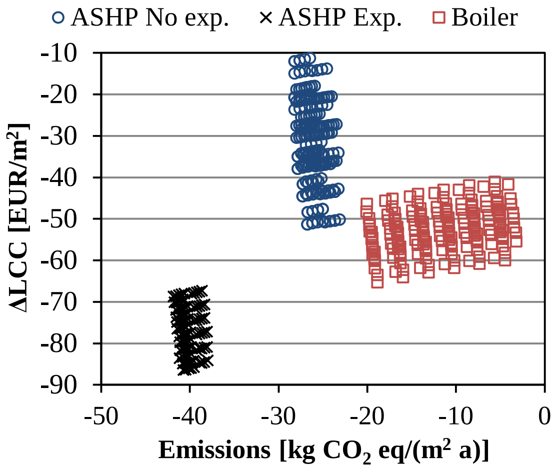

Figure B.1 – *The exploration of the lowest LCC systems on the fronts in the Dutch case with net-metering.*

B.2: Saturation of PV

Figures 4 and 6 show that investments in PV systems reach the maximum defined in this study in several cases. Thus, extended optimizations for the Netherlands and Finland have been conducted to investigate if larger PV systems would provide optimal solutions; the results of the previous and the extended optimizations for the Netherlands and Finland can be seen in Figure B.2. The maximum PV capacity has been increased to 20 kW, while the ranges for the rest of the variables remain unchanged; Figure B.3 shows the installed capacity of PV on the optimal fronts. Moreover, only the system with the lowest LCC is included, namely the ASHP system with heat export in the Netherlands and the GSHP system without heat export in Finland.

The results provide two remarkable outcomes. First, the optimal PV capacity does not lie within the 10-kW range given in this study, as the Pareto fronts from the 10-kW optimizations are dominated by the fronts of the 20-kW optimizations in all the explored cases. However, it must be underlined that single-family buildings usually have limited rooftop area, and thus installing large PV systems may be unfeasible; this is the case in the studied buildings. Second, systems with a LCC lower than in the previous optimizations were found for each case. This implies that the LCC optimum lied outside the variable ranges investigated in this study, and potentially lies even outside the extended PV range. These two outcomes reinforce the need to search for the optimal energy system based on the conditions particular to each building, such as available rooftop area and energy demand.

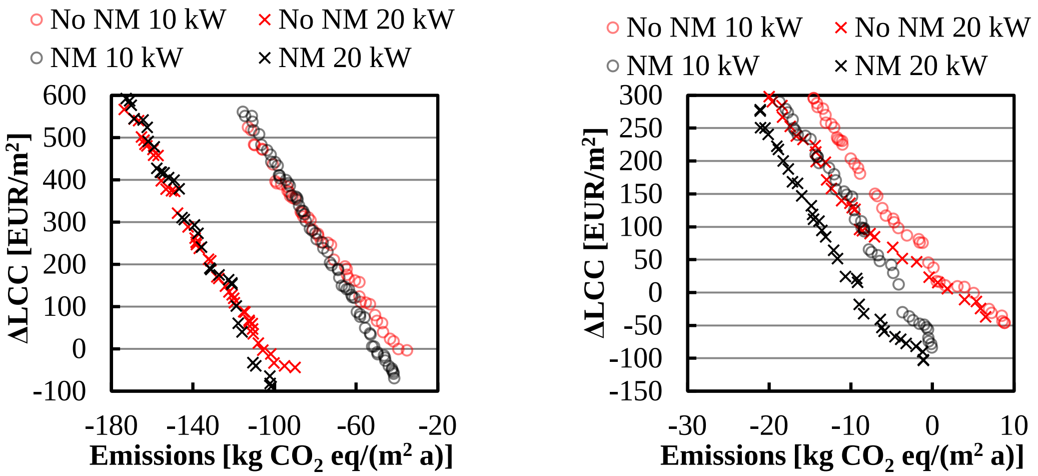

Figure B.2 – *The extended optimization with up to 20-kW PV for ASHP with export in Netherlands (left), and the extended optimization with up to 20-kW PV for GSHP without heat export in Finland (right), with (NM) and without (No NM) net-metering.*

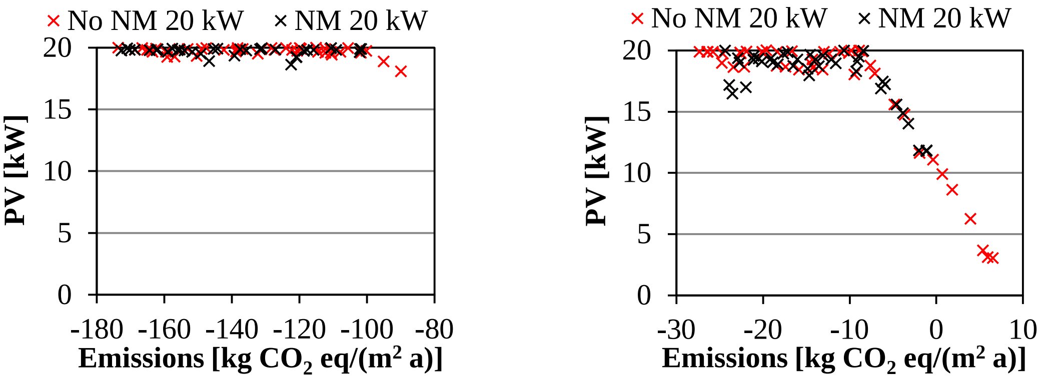

Figure B.3 – *The installed capacity of PV on the optimal front in extended optimization with up to 20-kW PV for ASHP with export in Netherlands (left), and the installed capacity of PV on the optimal front in the extended optimization with up to 20-kW PV for GSHP without heat export in Finland (right), with (NM) and without (No NM) net-metering.*