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Abstract

There is significant growth in the utilization of renewable energy in the built environment. Due to the intermittent nature of most renewable energy sources, energy mismatch problems between on-site generation and demand both in hourly and seasonal levels are unavoidable. This problem is more significant in Northern latitudes, as in summer there is high solar availability despite low or no electricity demand for cooling and in winter the solar availability is low when there is a high demand for heating. In addition, energy-pricing policies are leading to less or no Photovoltaic (PV) feed-in-tariffs in the near future and/or even providing incentives to uphold self-consumption. Therefore, it is important to enhance the energy flexibility potential of a building to improve utilization of on-site generated energy.

In this study, a performance optimization of various residential building designs with differences in energy demand, on-site energy generation and storage sizes is carried out considering future policy scenarios. The objective is to minimize the dependency to the nearby energy grid and maximize the self-consumption. To achieve this, a performance-based design support framework is proposed and demonstrated using a case study.

Introduction

The use of PV systems in the built environment shows a large increase in recent years, due to the introduction of financial support schemes for the building owners(Widén, Wäckelgård, and Lund 2019). Most European countries have initially started with production-based support schemes like feed-in tariffs (FiT). However, in several countries these schemes are replaced with schemes that promote self-consumption of locally produced electricity (Castillo-Cagigal, Caamaño-Martín, et al., 2011).

The large-scale introduction of locally produced electricity by PV systems cause major challenges for the electricity distribution grid operators (DSO), since most grids are not designed for managing both electricity demand and production. For example, large and frequent mismatches between local demand and local production can strongly affect the power quality at feeder level of the grid (i.e. at neighbourhood level). The DSO can alleviate these problems by increasing the capacity of the grid. Additionally, policy makers can alleviate these problems by introducing the aforementioned schemes that promote self-consumption, since these schemes give a financial incentive to the building owner to match their own demand with their own production which will decrease the import and export of electricity to the grid. These schemes support another solution which is the design of buildings that are *less dependent on the grid* compared to current buildings, e.g., by designing buildings with *low grid interaction*. These buildings should make clever use of building design (orientation, Rc-values, etc.), energy storage and demand-side management strategies to match their own demand and production. These buildings would be able to exploit the abovementioned incentive scheme, which is beneficial for the building owner.

Several studies investigate the energy matching and grid interaction aspects of buildings by studying the *energy flexibility* of buildings; this is for example one of the aims of the IEA EBC Annex 67 'Energy Flexible Buildings'. According to this Annex energy flexibility *is the ability of a building to manage its demand and generation according to local climate conditions, user needs, and energy network requirements* (Jensen et al., 2017). Several other studies focus on increasing self-consumption through the deployment of Demand Side Management (DSM) strategies (Widén, 2014; Williams, Binder and Kelm, 2012; Sossan et al., 2013; Clastres et al., 2010). Other studies focus on applying energy storages (Parra, Walker and Gillott, 2014; Braun, Perrin and Feng, 2009; Mulder, Ridder and Six, 2010), e.g., using electrical batteries to further improve load matching (Castillo-Cagigal, Gutiérrez, et al., 2011; Castillo-Cagigal, Caamaño-Martín, et al., 2011; Matallanas et al., 2012; Bruch and Müller, 2014). The literature study shows that currently there is no design approach available that takes into account the matching and grid interaction aspects of buildings during the design process.

This paper proposes a computational performance assessment methodology that integrates relevant energy flexibility indicators regarding energy matching and grid interaction. Furthermore, this paper shows how the assessment methodology can be used to design future-proof grid independent buildings by considering various policy scenarios (support schemes). The proposed design optimization approach is demonstrated using a case study of Dutch (residential) house and the building owner as the main decision maker/stakeholder. The details of the performance assessment methodology and the design optimization approach are discussed in the next section.

Design optimization for houses with low grid-dependency

The proposed design optimization approach consists of three main steps. These steps are presented below:

1a. Identify the decision makers' preferences and define the relevant performance indicators including energy matching and grid interaction performance indicators.
1b. Define the design space, e.g., define the possible renovation measures that should be considered (variations in building envelope properties, HVAC systems, size of onsite-energy generation system and storage systems).
1c. Formulate the future scenarios, e.g., in this paper based on the various support schemes.

2. Predict the performance of each design solution in the design space using building performance simulation and calculate the performance indicators across all future scenarios.
   In this paper the performance of each design is predicted using the building performance simulation tool TRNSYS. The performance of each design is assessed based on the defined performance indicators and the energy matching and grid interaction performance indicators. The performance indicators are often conflicting, therefore a multi-objective optimization approach is deployed with the objectives to minimize (or maximize) each indicator.

3. Analyse and present future-proof building designs with low grid dependency using multi-criteria decision-making.
   Due to the conflicting nature of most indicators, a set of Pareto optimal solutions is obtained for each scenario. This enables the decision maker to perform a trade-off among alternative design solutions based on the preferred performance indicators. Depending on the selected performance indicators, the set of Pareto optimal solutions can vary per scenario. It is assumed that the probabilities of the occurrence of the scenarios is unknown and hence, it is essential to assess the performance robustness of the design solutions considering all scenarios. The minimax regret method (Kotireddy, Hoes and Hensen, 2018) is used to calculate the performance robustness of each Pareto.

Case study description

A typical Dutch residential, semi-detached terraced house from 1975, (RVO.Nl) is chosen as the case study building. The building is a heavyweight three-floor construction as shown in Fig.1. Each floor is considered as one thermal zone for calculating the temperature and energy demand of each zone. The living room and kitchen at the ground floor form the first zone, three bedrooms in the first floor constitute the second zone, and the attic in the second floor is the third zone. Heating is supplied by air source heat pump and the building is ventilated with balanced mechanical ventilation with a heat recovery unit. Natural ventilation (free cooling) is used in summer instead of mechanical cooling (Kotireddy, Hoes and Hensen, 2018).

Identify decision makers and performance indicators

The decision maker of this case study is the homeowner. The homeowner wants to renovate his house and requires a comfortable indoor environment at low investment and operating costs. The considered performance indicators are described in Table 1. In order to assess the energy matching and grid interaction of each design the indicators as described in Table 2. are defined.

Table 1. Overview of thermal comfort and costs performance indicators.

Figure 1. Layout of a typical Dutch terraced house, showing different floors, front and back view of the building. All dimensions are in mm.

Name	Mathematical description	Characteristic
Weighted overheating hours (WTOH)	$WTOH = \Delta T * h$ h: total number of hours exceeding the allowable maximum indoor temperatures ΔT: degree of temperature excess	Indicating number and magnitude of hours exceeding the allowable indoor temperatures, based on maximum and minimum acceptable indoor temperatures as proposed on (Peeters *et al.*, 2009)
Operational cost (OC)	$OC = (E_{import} * P_E + NG * P_{NG}) - (E_{inc} * P_{inc})$ E_{import}: imported electricity from grid, P_E: price of electricity, NG: natural gas, P_{NG}: price of natural gas, E_{inc}: type of energy receives incentive, P_{inc}: rate of incentive	Annual energy costs for gas and electricity consumption. Exported or self-consumed electricity is also considered in the calculation of operating cost, depending on the policy scenario
Additional investment cost (IC_a)	$IC_a = \sum IC_{design_{options}} - \sum IC_{reference_{building}}$	Additional amount of required investment in comparison to reference

Table 2. Overview of energy matching and grid interaction performance indicators

Name	Mathematical description	Characteristic
On-site Energy Matching (OEM)	$\dfrac{self-consumption\ [kWh]}{on-site\ generation\ [kWh]}$ Self-consumption and on-site generation are integrated over summer months	Describe the degree of the utilization of on-site energy generation related to the local energy demand (Salom *et al.*, 2014).
On-site Energy Fraction (OEF)	$\dfrac{self-consumption\ [kWh]}{Energy\ demand\ [kWh]}$ Self-consumption and energy demands are integrated over winter months	Show the effectiveness of on-site generation, how often demand is lower than supply and how often supply is lower than demand.
Grid dependency (Huang, Huang and Sun, 2018)	$\dfrac{\Gamma power\ exchange \neq 0}{\Gamma total}$ Γ : number of time	Represents the frequency of either positive or negative power exchange between a building and the power grid.
Capacity factor (Verbruggen and Driesen, 2015)	$\dfrac{energy\ exchange\ with\ the\ grid\ [kWh]}{nominal\ connection\ capacity\ [kW]*period[h]}$	Indicates the total energy that has been exchanged with the grid (either supply to or import from the grid) in ratio to nominal connection capacity

Define the design space

Different design options, as shown in Table 3, are varied to form the design space. In order to satisfy different building standards, design options related to building envelopes such as window type, insulation level of envelopes and infiltration rates are altered at the same time and formed different renovation packages. First renovation package, RP1, meets the energy label B requirements. RP2 is based on the current Dutch building standard ("*Corner house (M)*"). RP4 and RP5 can meet Dutch zero-energy buildings standard ("*Corner house (M)*")and a Passive house standard in respect. Hence, the air to water heat pump system is sized for each building envelope package. Other design options such as size of PV system, size of electrical battery and type of DHW system are varied for all building envelope packages.

PV panels with a module efficiency of 18% and an inverter with a conversion efficiency of 97.5% are chosen for the on-site energy generation system ("Canadian Solar"). The size of PV system is varied from 5m² to 25 m² for all building envelope packages where the maximum size of PV system is limited by the available roof area on the south surface. Each panel has a gross surface area of 1.67 m² and a peak capacity of 260 Wp. As it is shown in Table.3, the sizes of the electrical battery capacity (*sonnenBatterie*), with 2.5-3.3 kW charge and discharge power, is changed for each building envelope packages.

Two different systems are assumed to meet the domestic hot water (DHW) needs, one is a standalone solar domestic hot water system with an electrical auxiliary heater and the other one is a gas boiler. Both solar thermal

collectors and photovoltaic panels are placed at a tilt angle of 43° facing south, which is also the slope of roof.

Table 3. Considered Design parameter options

Renovation package	Reference	RP1	RP2	RP3	RP4	RP5
RC-floor, m²k/W	1.3	2.5	3.5	5	6	10
RC-wall, m²k/W	1.3	2.5	4.5	7	8.5	10
RC-roof, m²k/W	1.3	2.5	6	8	10	10
Window U value, W/m²K	5.2, 2.9	1.8	1.43	1.01	0.86	0.52
Window g value	0.81, 0.75	0.61	0.60	0.38	0.59	0.58
Infiltration, dm³/sm²	1	0.62	0.5	0.4	0.15	0.1
ASHP nominal capacity, kW_th	9.1	7.4	6.0	4.9	4.0	3.5
PV system, m²	5, 10, 15, 20, 25					
Electric battery, kWh	0, 2.5, 5, 7.5, 10, 12.5, 15					
DHW system	Solar thermal collector (STC), HR 107 gas boiler (GB)					

In this study, the system supplies the required load by prioritizing first the electricity generation from PV panels and second from battery and finally from the grid. The surplus on-site generated energy will be supplied to the battery and in case that battery is full will be sent back to the grid.

Define future scenarios

Various types of support schemes are currently in operation in different countries. Most of the European countries have initially started with production-based support schemes like feed-in tariffs (FiT). In this scheme, the PV system owner receives a fixed rate for each unit of electricity (kWh) fed into the power grid. Other support schemes are based on self-consumption support mechanisms where energy saving and the use of on-site generated electricity are rewarded instead of rewarding the export of electricity. In these type of schemes, typically the exported electricity is sold at low prices whereas the price of the purchased electricity is high. Therefore, a mismatch between on-site generation and demand can cause a financial loss to the PV owner. Thus when these schemes are in place, it is beneficial for the PV owner to match the building's on-site electricity generation with the electricity demand as much as possible.

The scenarios below are selected to give an overview of possible future policies ranging from production-based support to self-consumption based support schemes. The considered scenarios are as follows:

1. **Net metering scenario**: energy imported from grid and on-site produced energy exported to the grid are measured and their difference determines the electric bill, though negative bills might not be allowed. (Hirvonen *et al.*, 2015).

2. **Guaranteed FiT**: a fixed rate is paid for each unit of electricity generated and supplied to the grid.

3. **Self-consumption incentives:** provide money if locally generated energy be used on-site, instead of being exported to the grid.

4. **NO incentive**: there will be no incentive for energy fed into the grid or used locally

Type of support scheme	Policy scenario	Rate of incentive (c€/ kWh)	Electricity price (c€/ kWh)
Production- based incentive	Net- metering	$\frac{17.06 \ c€}{kWh \ electricity \ fed \ to \ the \ grid}$ As long as : $\sum_{Year} exported_{energy} \leq \sum_{Year} imported_{energy}$	17.06
	Guaranteed FiT	$\frac{8.53 \ c€}{kWh \ electricity \ fed \ back \ to \ grid}$	17.06
Self-consumption promoting	Self-consumption based	$\frac{17.06 \ c€}{kWh \ electricity \ demand \ met \ by \ own \ generatio}$	17.06
	No incentive	$\frac{0 \ c€}{kWh \ electricity \ either \ fed \ to \ the \ grid \ or \ consumed \ locally}$	17.06

Performance prediction and analysis of the design solutions

The performance of each design solutions is calculated for all four policy scenarios. However, in this section, first the results are described for the current energy policy scenario in The Netherlands, the net-metering scenario. The results for the other scenarios including the robustness analysis is presented in the next section.

Performance under the current net-metering scenario

Figure 2a shows the additional investment cost, the operational cost and the weighted over heating hours of all design solutions. Each dot represents the performance of a unique design solution, i.e., a unique combination of the building envelope and infiltration rate, PV system size and electrical storage capacity. To get a better insight of the design variants, RC-values of the walls, the size of PV system and electrical storage capacity are indicated with colors in the scatter plots in Figures 2b, 2c and 2d.

The figures show that operational cost decreases with higher RC-values and lower infiltration rates, while the number of overheating hours and additional investment cost increases. One can easily distinguishes the effect of the size of the PV system on the operational cost; however, the storage capacity does not influence the operational cost for this policy scenario. In this scenario the user will sell the surplus of on-site produced electricity to the grid at the same rate of buying from the grid. Hence, under this policy scenario, the grid is used as a virtual, unlimited electrical storage device. The designs with the variations in electrical storage capacities only differ in investment cost.
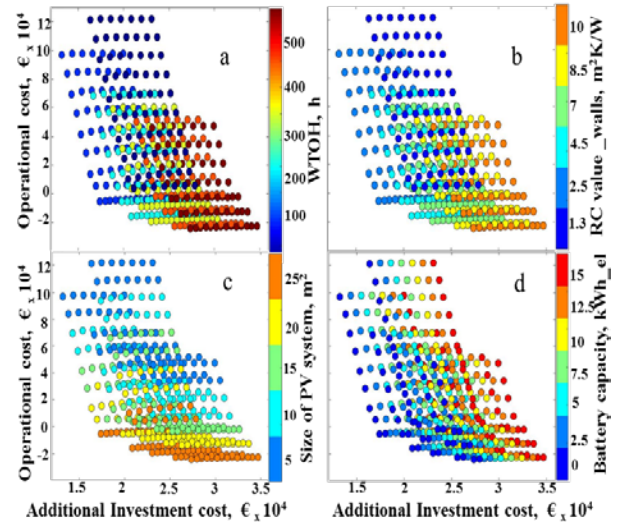

Figure 2.The investment cost and operational cost for total energy consumption of all designs solutions under net-metering scenario

Figure 3 shows the energy matching and grid interactions indicators of the design space against the operational cost and the additional investment cost. Comparing Figures 3a and 3b and the design parameter variations in Figures 2b, c and d, gives some insight about the self-consumption potential of each design solution. The designs with a small PV system reach a higher OEM regardless of the insulation level and infiltration rate of the building (which mainly decide the energy consumption of the designs). However, this happens at the expense of higher operational cost in comparison to the designs with larger PV systems. Designs with high insulation levels [8.5-10 m²K/W] and low infiltration rates show better OEF, since these designs have a very low energy consumption, especially when they are equipped with high number of PV panels and a high electrical storage capacity. These designs operate at very low operational cost; however, they require very high investment cost.

Figures 3c and 3d illustrate the performance of design solutions regarding the frequency and the magnitude of the traded power with the energy grid. Figure 3c shows the effect of the storage capacity on number of times that a design will interact with the grid; designs without electrical energy storage are almost fully dependent on the grid [grid dependency ≥0.9]. The figure shows that the dependency on the grid can be reduced to less than 0.5 for the buildings with low energy consumption [8-10 m²K/W] accompanied with large PV systems [20-25 m²] and high storage capacities [10-15 kWh]. The high on-site energy generation can easily meet the demand of these buildings, while the high storage capacity helps to bridge the gap between demand and generation instead of exporting the surplus electricity to the grid.

Designs with high insulation levels typically have low power consumption for space heating demand and consequently the sized air to water heat pumps have low power capacity. These designs along with a small sized PV system use the minimum capacity of the designed power with the grid as it can be observed in Figure 3d.
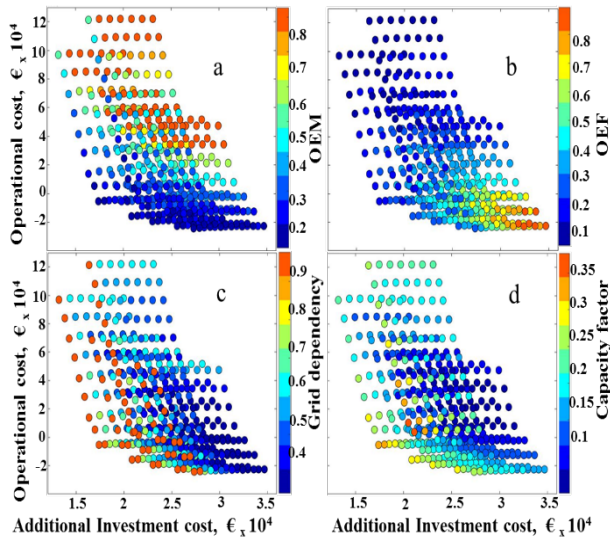
Figure 3. Performance indicators, investment cost and operational cost for total energy consumption of all design solutions under net-metering scenario.

Overall, the designs with low RC-values and high infiltration rates show low overheating hours, but at the expense of high operational cost. Because of their high-energy consumption, they utilize a higher ratio of on-site produced energy (high OEM). However, this is not enough to meet a noticeable amount of energy consumption (low OEF) and consequently they show high and frequent interaction with the grid to satisfy the demand. Similarly, the designs with high RC-values and low infiltration rates (e.g. passive house) are characterized by very low energy demand and higher overheating hours. These designs can reach high OEF and very low capacity factors. However, because of the low energy consumption, they do not utilize the on-site production efficiently (low OEM). The designs with intermediate RC-values [2.5-4.5m^{2}K/W] and infiltration rates are having optimal performance in terms of thermal comfort and show moderate operational and investment costs. These designs can utilize on-site production efficiently to meet the demand when they are equipped with appropriately sized of PV systems and storage capacities.

The Pareto solutions (the trade-off solutions; the solutions that perform equally good) can be calculated considering various sets of performance indicators. The dark blue colored dots in Figure 4.1 show the Pareto solutions in case the homeowner is only interested in operational cost, investment costs and thermal comfort. The cyan colored dots shows the Pareto solutions in case the homeowner only considers the energy matching and grid interaction indicators. As expected, these two sets of Pareto solutions are quite different under this net-metering scenario, since the scenario does not provide any (financial) incentive to the homeowner to invest in a house with low grid dependency.

Building performance considering all policy scenarios

The previous section showed that there was no incentive for the homeowner to consider low grid-dependency. However in the future the policy scenario is likely to change. This section shows the performance of the design solutions considering all four policy scenarios.

Furthermore, it is discussed which design solutions are the most robust performing considering these scenarios.

As discussed above, Figure 4.1 shows the two Pareto solution sets considering policy scenario 1. The Pareto sets for scenarios 2, 3 and 4 are presented in Figures 4.2, 4.3 and 4.4. The figures show that the gap between the two Pareto sets is more significant in scenarios 1 and 2 (Figures 4.1 and 4.2), which indicates that the solutions with low grid-dependency are not (financially) attractive to the homeowner under these production-based incentive policies. The reason is that, in these scenarios by selling back the produced energy to the grid, the homeowner can significantly reduce the operational cost. The two sets of Pareto solutions come closer in Figure 4.3, the self-consumption based incentive, and even closer in Figure 4.4, where there is no incentive at all. In these scenarios the more profitable designs for the homeowner are also the ones with higher self-consumption, i.e., lower grid-dependency.
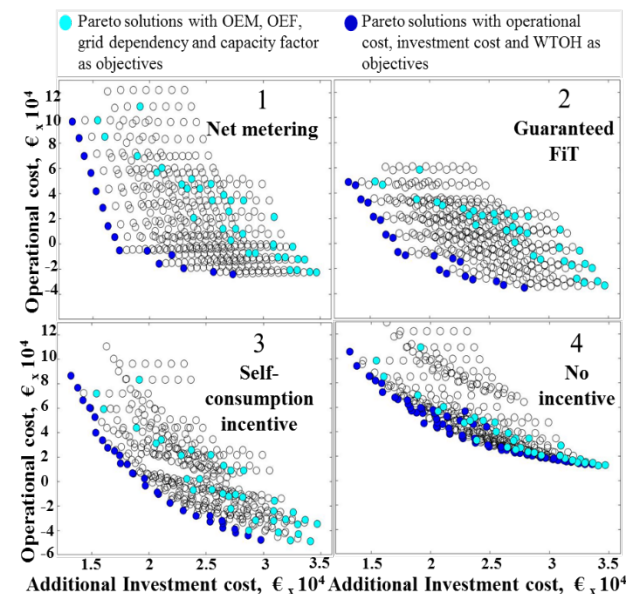

Figure 4.Two sets of Pareto solutions are presented per graph: dark blue dots represent the Pareto solutions based on operational cost, investment cost and overheating hours. Cyan coloured dots represent the Pareto solutions based on the energy matching and grid interaction indicator

Figures 5 and 6 present with colors the values of the design parameters for the solutions of both Pareto sets. The Pareto solutions based on additional investment cost, operational cost and overheating hours are represented with the coloured dots with light-grey edges (from here on refered to as the homeowner set). The Pareto solutions based on energy matching and grid interaction are represented with coloured dots with the black edges (from here on refered to as the energy flexibility set or EF set). These designs show a trade-off between thermal comfort and operational and investment cost. The Pareto solutions of the EF set show a larger variation of insulation levels; however, the majority of the designs is based on high insulation levels and low infiltration rates. In production-based incentive policies, Figure 5, the operational cost decreases with larger PV systems.
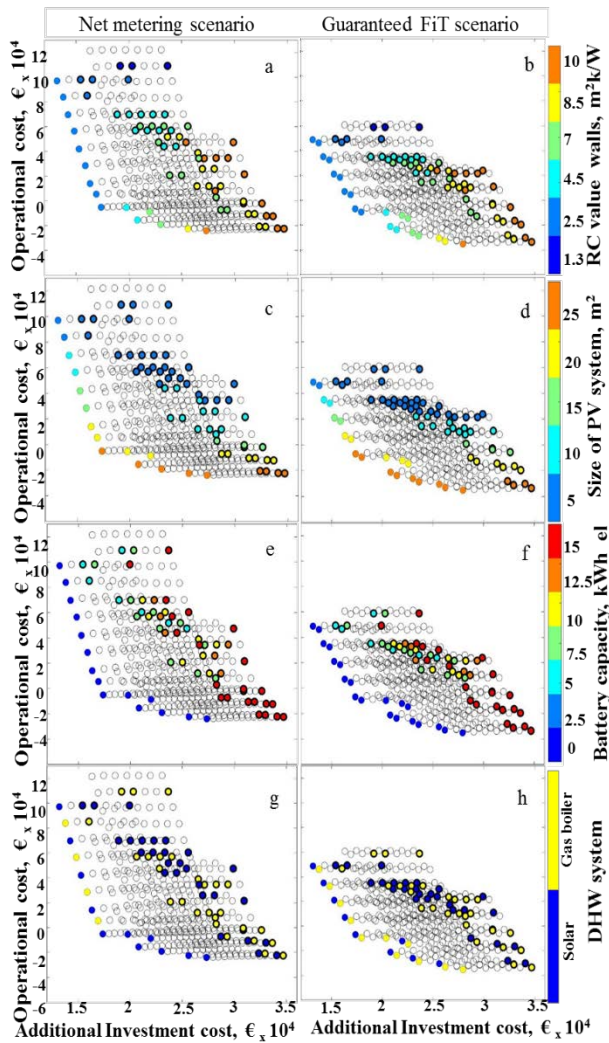
Figure 5. Two sets of Pareto solutions for the production-based incentive policies (scenarios 1 and 2). Dots without edge represent solutions based on additional investment cost, operational cost and overheating hours. Dots with black edged-lines represent solutions based on energy matching and grid interactions.
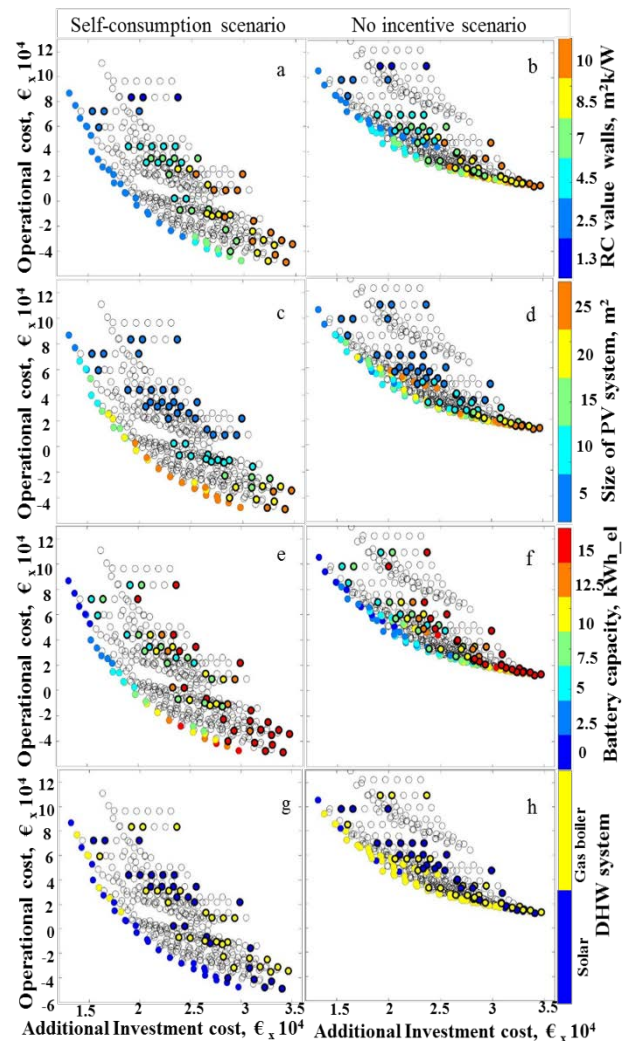

Figure 6. Two sets of Pareto solutions for the self-consumption-based incentive policies (scenarios 3 and 4). Dots without edge represent solutions based on additional investment cost, operational cost and overheating hours. Dots with black edged-lines represent solutions based on energy matching and grid interaction.

Since there is a financial compensation for every kWh of on-site produced electricity fed into the grid, the solutions in the homeowner set show zero storage capacities and large PV systems. Figure 6 shows that in the self-consumption-based policies, the size of storage capacity in homeowner Pareto set increases with the size of PV system in order to increase the self-consumption of on-site produced electricity consequently reducing the operational cost.

Future-proof building designs with low grid dependency considering all policy scenarios

Some design parameters can be replaced relatively easy at any time, such as the size of the electrical storage, while some other design parameters are not easy to change after the renovation, such as the building insulation level. Accordingly, it is useful for the homeowner to understand how robust each design option performs across the policy scenarios. This information is provided by calculating the performance regret for each solution. Figure 7 shows the

influence of a chosen design parameter value on the predicted performance of the other homeowner Pareto set solutions.

Each boxplot show the performance spread for a design parameter value caused by variations in all the other design parameters and by the scenarios. For example, the first boxplot (RP1-STC) is the building design with Renovation Package 1 (RP1) equipped with a Solar Thermal Collector (STC) connected to the DHW system. The performance spread is caused by the variations in the remaining design parameters, in this case by the PV system sizes and the battery sizes. The figure shows that the performance regret of the operational cost decreases with larger sized PV systems and larger electrical storage capacities (bottom graph), which is because by the increase in utilization of on-site produced electricity. It can also be observed that designs with a gas boiler DHW system result in lower performance regrets across the considered scenarios for RP3 and RP4 in comparison to designs with solar DHW
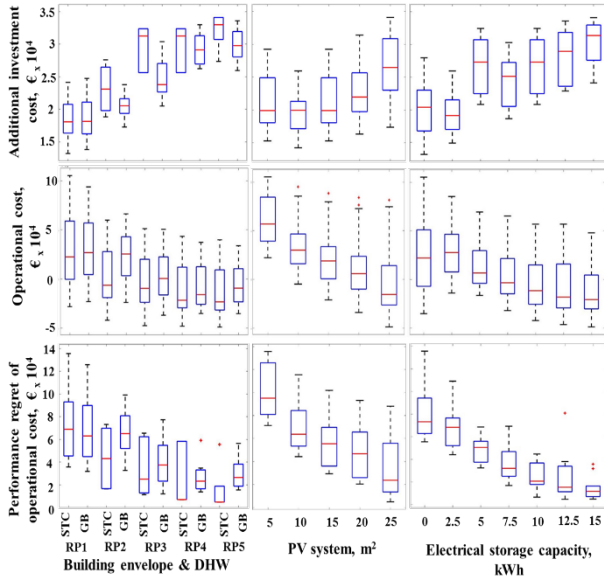
Figure 7.The boxplots show the performance spread for a design parameter value caused by variations in all the other design parameters and by the scenarios. The presented solutions are from the homeowner Pareto set.

Figure 8.The boxplots show the performance spread for a design parameter value caused by variations in all the other design parameters and by the scenarios. The presented solutions are from the EF Pareto set.

system. Designs with higher insulation level and lower infiltration rates have generally lower space heating demands, hence the share of energy consumption due to DHW demands are getting more weight in total energy consumptions.Hence, the designs with higher insulation level can get lower variations of operational cost and consequently lower operational cost regrets with gas boiler DHW system.

The bottom graph of Figure 7 shows that designs with building envelope RP1 have larger variations of the performance regret for operational cost compared to the designs with building envelope RP5. This indicates that the operational cost of RP5 is more robust across the considered scenarios. However, it requires higher additional investment costs compared to other packages (refer to top graph of Figure 7).

The homeowner might prefer the building envelope RP2 equipped with solar DHW system, which has similar regret variation as RP3 and RP4 with solar DHW, but it requires a lower additional investment cost. Considering variations in operational cost and corresponding performance regrets, the homeowner would prefer larger PV systems and larger electrical storage systems.

Figure 8 shows the influence of a chosen design parameter value on the predicted performance of the EF Pareto set solutions. Note that some design parameter values are not included in any of the Pareto solutions, e.g., the battery size of 0 kWh. The figure indicates that designs with intermediate insulation levels [2.5-4.5 m^2K/W] result in a higher range of operational cost and higher operational cost regrets in comparison to same design options in the homeowner Pareto set. The EF Pareto solutions are equipped with electrical storage capacities of 5 kWh or higher. As mentioned, low electrical storage capacities [0-2.5 kWh] are not included in this set of Pareto solutions. High electrical storage capacities are not as robust as in the homeowner Pareto set (compare to Figure 7). However, in
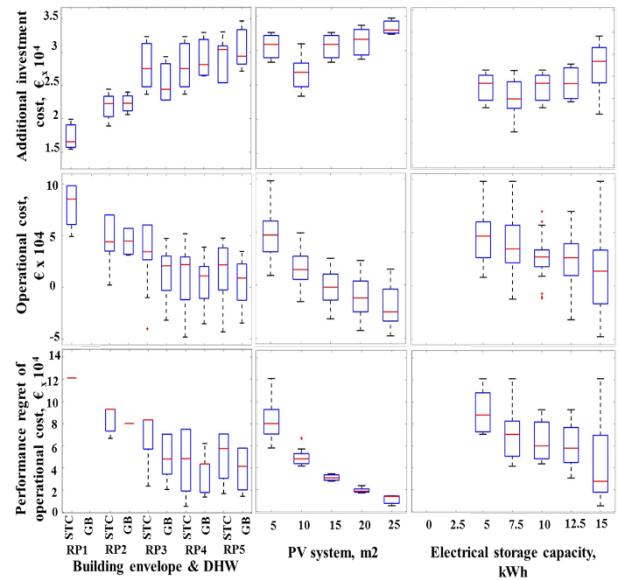
the EF Pareto set the variations of operational cost and its corresponding regrets can be reduced with higher size of PV systems. As is shown in Figure 8, the larger PV systems result in very low performance regret for operational cost in expense of high investment costs.

Overall, considering variations in operational cost and corresponding performance regrets, designs with high insulation levels [8.5 m^2K/W], large PV systems [25 m^2] and high storage capacities [15kWh] are dominating the EF Pareto set, however because of the high additional investment cost these solutions might not be the homeowner's preferred design solutions.

Conclusion

This paper presents a simulation based design optimization methodology in identifying building designs with improved energy flexibility potential to increase the utilization of on-site generated energy and to reduce the dependency to the energy grid. This methodology integrates uncertainties due to policy scenarios in multi criteria assessment to aid decision makers in selection of robust design options.

Results show that proposed methodology provides decision maker information to trade off investment in improving building insulation levels with the other design options like electrical storage and PV system. In addition, decision maker (as here is homeowner) can choose design options that are more robust to the preferred performance indicators.

As it is observed in this case study, energy flexible designs able to provide higher self-consumption and lower dependency to the grid are more expensive for homeowners specifically in policy scenarios providing incentives to on-site produced energy. However, these designs are more profitable in probable future policy scenarios promoting self-consumption.

Further work will aim at extending the proposed methodology to assess the performance of groups of residential buildings considering energy flexibility potential in increasing local self-consumption and in reducing grid dependency.

Acknowledgement

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