Optimization of Air Source Heat Pump Systems over the Heating Season through the Use of Renewable Energy Sources

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ABSTRACT

The drive to cover with renewable energy sources an increasing quota of the energy use of a building is boosting the installation of heat pumps coupled with PV panels for residential heating applications. This HVAC solution is especially advantageous in high performance buildings when low temperature hydronic systems (e.g. radiant panels) are adopted. Nonetheless, the seasonal performance of the heating system is strongly dependent on HVAC design choices, such as the system sizes (heat pump, water storage tank, PV battery), and on the system control strategies adopted. Besides, if too many heat pumps are installed an unbearable burden may be imposed to the national power grid. Thus, an optimal design and control of the heating systems installed in high performance building is essential to ensure, along the entire heating season, not only a low energy use but also the appropriate exploitation of in-situ available renewable energy sources. This study presents a possible approach to the optimization of different system configurations, storage and control strategies for high performance buildings. A massive building located in the northern part of Italy has been considered to perform a preliminary application of this approach. The dynamic simulation of the building and its heating system was set up using the TRNSYS simulation suite and the optimization of the HVAC systems was performed coupling the simulation code with a Genetic Algorithm, to minimize the total energy consumption. Results highlight the role of thermal and electrical storage to optimize self-consumption and enhance the energy performance of air source heat pump. Besides, the study points out the issues of coupling systems with high response time in high performance buildings.

1. INTRODUCTION

This work aims to optimize the design of a heating system that includes PV panels and an air-source heat pump, two currently widespread technologies used to optimize the exploitation of renewable energy. The risk of covering heating needs with renewable energy is to overlook the objective of limiting energy use, the latter being not proportional to operating costs as in the case of fossil fuels. On the other hand, using renewable and zero emissions energy sources, the mere minimization of the energy needs of a building is not necessarily the only goal. Consequently, a multi-objective evaluation can be more appropriate in order to define optimal design solutions, although it is difficult to establish the right objective functions. Since the overall performance of such a system is strongly dependent on the weather and on the building load, each optimization has been made setting these two pre-conditions. In this preliminary application of the approach, the weather conditions of Trento, as representative of a climate of Northern Italy, have been considered. Regarding the building load, four different cases have been analyzed, based on two reference building types. The final purpose is to investigate the difference in the optimization results for different reference buildings and, in addition, the extent to which variations of some features of the envelope affects the optimal configuration of the HVAC system.

2. METHODS

2.1 General Approach

The work deals with the challenging of correct design and operation of air source heat pump (ASHP) coupled with photovoltaic (PV) systems. The choice of optimal trade-off between low energy consumption of ASHP and high PV integration without oversizing the PV system is based on the domination of a general solution X over a solution Y. According to Pareto, a solution X is said to dominate the other solution Y if both the following conditions are true:

1. The solution X is no worse than Y in all objectives;
2. The solution X is strictly better than Y in at least one objective.

Thus passing from Y to X an improvement for all the objectives is supposed, or an improvement for some, without the other ones be harmed. In other words, the concept of "Optimum of Pareto" simply indicates a situation in which it is impossible to improve the situation of an objective without making worse the others. The two steps of the optimization procedure are therefore the definition of the Pareto front and the selection of a trade-off solution among the Pareto front. For the multi-objective optimization (MOO) analysis of the building retrofit, an Elitist Non-dominated sorting genetic algorithms (NSGA-II) (Deb 2002) was implemented in MatLab (Penna *et al.*, 2014). The fitness function used in the analysis is a Matlab code that launch Trnsys model for the building energy simulation. After the model execution, the function reads the TRNSYS output file and post-processes the results of the simulation in order to compute the objective functions. In particular, the energy demand for heating, the fraction covered by PV power and the PV overproduction are chosen as goals for the MOO. The choice of these objectives aims at achieving the enhancement of the integration among HVAC components. In fact, by decreasing the energy consumption of the heat pump it becomes more difficult the achievement of a minimum value or renewable coverage factor avoiding the PV oversizing.

2.2 Genetic Algorithm Implementation

The implemented GA is an Elitist Non-dominated sorting GA algorithms (NSGA-II) (Deb, 2002). Nonetheless several customization of the code are used such as sampling, crossover, mutation and selection procedure. These adjustments coupled with the selection of mutation rate, population size, crossover fraction are adopted with the purpose of increasing the GA performances.The first step in the GA procedure is the selection of the initial population. The GA optimization is closely related to the initial population. In this regard, random sampling could lead in oversampling of same region, whereas a uniform random number generation produces uniform sample when the population size is high (Saltelli *et al.*, 2004). For this reason, the code was equipped with a Sobol´s sequence sampling in order to overcome the clustering which can occur with sample random sampling or quasi random generator (Saltelli *et al*., 2004). Sobol' sequence is a low-discrepancy sequence, which aim to give a uniform distribution of values; in higher dimensions (Burhenne *et al.*, 2011). The random starting point in the Sobol´ sequence was obtained through a pseudo-random generator (Matsumoto and Nishimura, 1988). Once the fitness function is evaluated, the GA proceeds with the selection of the best individuals. Selection is the procedure by which GA chooses parents for the next generation. In this study we adopted the tournament selection without replacement (TSWOR) (Goldberg *et al*., 1989, Golberg and Deb, 1991). In this method a short list of 4 eligible parents are randomly chosen and the best individual out of that set to be a parent. Following on from this point, the code combines the genetic characteristics of both parents, giving rise to the new generation. The recombination procedures implemented is based on arithmetic weighting of parents' genes to create children. Children are a random (Matsumoto and Nishimura, 1988) arithmetic mean of two parents, uniformly on the line between the parents. (Burjorjee, 2013). The adopted crossover fraction, i.e. the fraction of the next generation that crossover produces is set equal to 0.8. The remaining individuals in the next generation becomes from mutation of population. Mutation is applied at a random point in a random individual. In particular, by means of Mersenne-Twister pseudo random generator (Matsumoto and Nishimura, 1988), a randomly selected gene is replaced by a uniformly distributed random value that meet the gene range.

2.3 Test Cases

Two typologies of building are investigated (Figure 1) with the purpose of extending the representativeness of the analysis. In particular, a penthouse-like house (S/V = 0.63) and an intermediate flat in a multi-story building (S/V=0.3) have been considered. Also the orientation of the glazed façade was varied: south and east oriented windows have been considered. Overall, four test cases were selected; these buildings were developed starting from a reference building module, which is a typical flat having 100 m^2 floor surface, 3 m internal height and façades oriented towards the main cardinal directions (Penna *et al*., 2015).

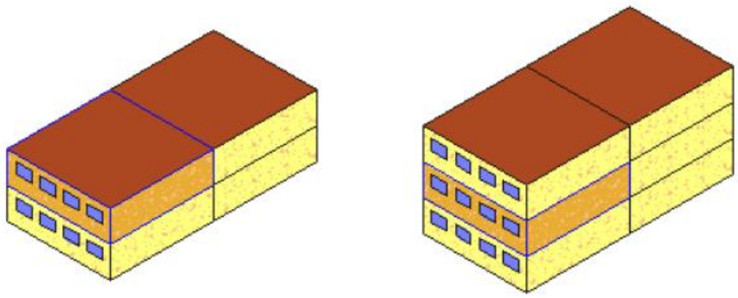


Figure 1: Building typologies used in the GA procedure (Penna *et al*., 2015).

2.4 Simulation of building-plant system

The dynamic behavior of the system was calculated by means of TRNSYS simulation (Figure 4). The reference heating system is based on an ASHP with variable speed compressor, coupled with radiant floor panels. A water storage tank separates the circuit of the water heated by heat pump and radiant panels loops, on which a circulation is installed. Therefore, the total electric load is the sum of power needed by heat pump (compressor) and circulation pump. The system is powered both by grid and photovoltaic electric power. Two different approaches for handling battery storage were implemented: the parameter "*mode*", defined internally in the simulation project, states which one is applied. In the first strategy (*mode*=0) the PV array is operated in parallel with the grid and the priority is to cover the load with direct photovoltaic power. The excess power is delivered to the batteries until they are fully charged, then is passed to the grid. When the PV are not generating power anymore, the available energy stored in the batteries is used. The second operation mode (*mode*=1) is an UPS like mode that avoids operation of the batteries in parallel with the grid but favors complete battery charge and discharge cycles. The system is connected to the grid only when the battery has been completely discharged and is disconnected when the battery has been fully charged. Figures 2 and 3 better explain these two approaches showing power output management for three representative days within the simulation period (Dec, 30th – Jan, 1st).

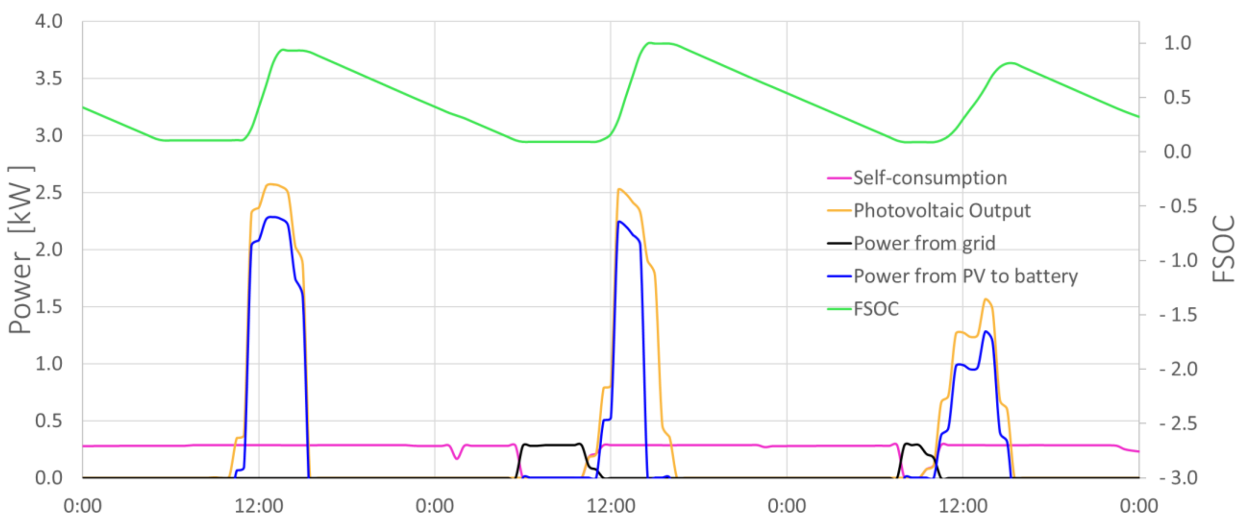


Figure 2: Power managing strategy corresponding to *mode*=0 (PV in parallel with the grid)

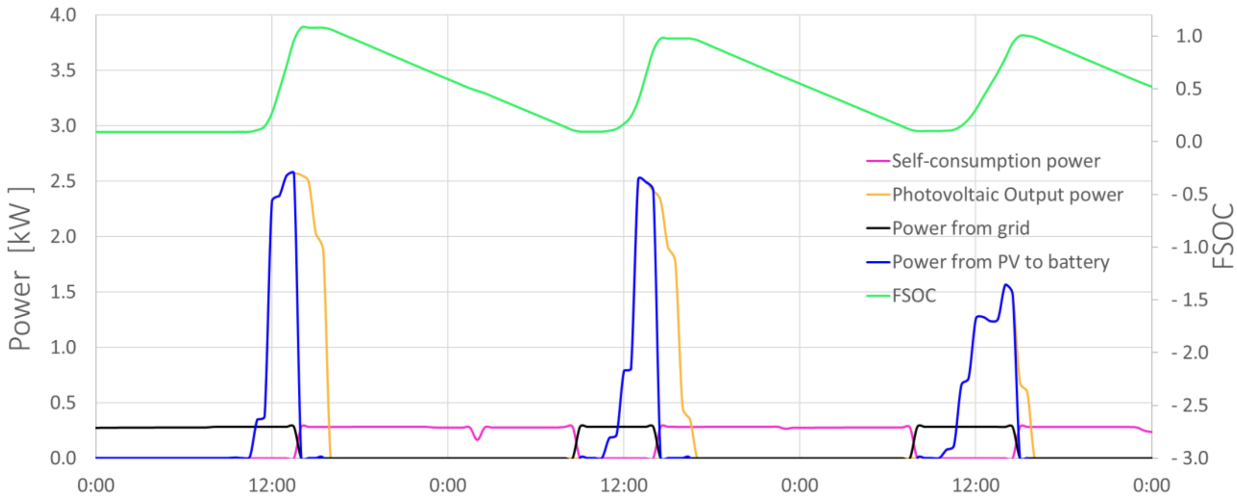


Figure 3: Power managing strategy corresponding to *mode*=1 (UPS mode)

The variable speed heat pump model used in the simulation program TRNSYS is described in (Bee *et al*., 2016). It takes into account the typical function of performance (f_{corr}) of commercial products for part load working conditions. The model allows to modify that function by means of two factors, that have been set as optimization parameters in the present work (see Table 1). The first parameter is the CR value where the COP begins to degrade; the second is the CR value where the maximum of f_{corr} occurs (this last set to 1.2, as can be the case with the last generation of variable speed heat pumps commercially available). Also the rated thermal power and the rated COP (both referred to 7-35°C) are variable parameters. Thermal power and compressor power at different reference temperatures are given in input to the model as fractions of respective rated values. The photovoltaic array has been described with type 194 in the TESS library. This model is based on the calculation method presented by De Soto *et al*., 2006. Performance specifications of photovoltaic modules are representative of high efficient products currently used in residential applications. The output of interest from this component is the electrical power, that, at every simulation time-step, can be used in different ways, depending on the described approaches. The number of modules is an optimization parameter and each module has an area of 1.6 m^2. The battery was defined with type 47, a model of a lead-acid storage battery that operates in conjunction with solar cell array and power conditioning components. It specifies how the battery fractional state of charge (FSOC) varies over time, given the rate of charge or discharge. A minimum FSOC (0.1) has been set so that the model is consistent with real applications, being the complete discharge of the battery not recommended. The capacity depends on the total numbers of cells, each having a capacity of 1.2 kWh. Radiant floor panels are defined within the building model as an active layer (Solar Energy Laboratory, 2005). Radiant floor design refers to a typical commercial configuration: pipe spacing 0.12 m, pipe outside diameter 0.016 m, pipe wall thickness 0.002 m and pipe wall conductivity 0.44 W $m^{-1}K^{-1}$. The system is equipped both with climatic and zone control. Climatic control changes the supply water temperature as a linear function of the outdoor air temperature. The curve can be modified throughout the optimization process, by means of two parameters: the supply water temperatures corresponding to outdoor air temperatures of 18 °C and -5 °C (plant operation limits for the considered reference year). If the heat pump reaches his lower modulating limit and water is warmed up more than necessary, an on/off controller turns it off. This controller works with a dead-band, which width was optimized. The zone control is handled by a proportional band thermostat (type 1669) with a variable set-point and a band width of 0.5 °C or 1°C (optimization parameter). Set-point can be adjusted between 19 °C and 22 °C during the day and between 15 °C and 19 °C during the night. Also the hours when the set-point changes are parameters to be optimized. Thermostat output signal controls the flow rate circulating in the radiant floor loops, that can vary from 0 kg/h to the maximum design flow rate (400 kg/h). Finally, the building has been modeled by means of the TRNSYS Multi-zone Building subroutine, type 56. Envelope features and considered test cases are described in the previous paragraph. The complete list of optimization parameters previously mentioned is reported in Table 1. Figure 4 represents a schematic view of the system, as in the Simulation Studio TRNSYS tool.

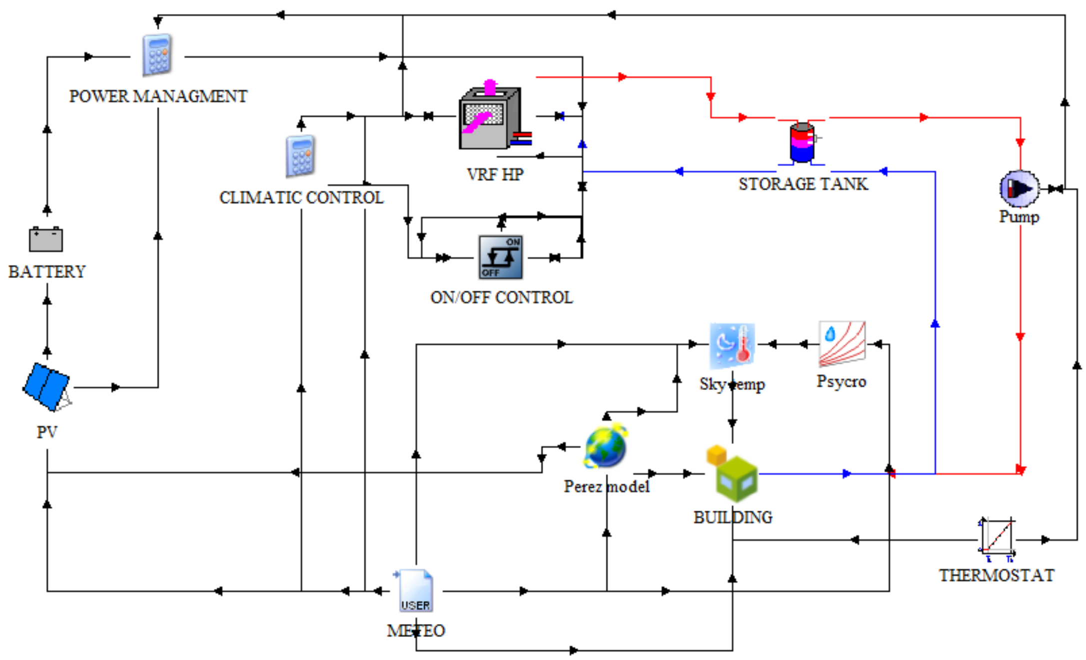


Figure 4: Building and heating system model (TRNSYS)

Table 1: Optimization parameters

Description	Units	Minimum value	Maximum value	Variation step
Tank volume	m^3	0.05	2	0.05
Climatic regulation curve - parameter 1	°C	25	30	1
Climatic regulation curve - parameter 2	°C	30	40	1
Dead band half width for HP on-off controller	°C	0.5	2.5	0.5
Dead band half width for thermostat	°C	0.25	0.5	0.25
HP rated thermal power at 7-35 °C	kW	4	10	0.05
HP rated COP at 7-35 °C	-	3.5	5	0.1
HP part load function – parameter 1	-	0.2	0.4	0.05
HP part load function – parameter 2	-	0.45	0.6	0.05
Number of photovoltaic modules	-	2	12	2
Number of battery cells	-	4	16	4
Mode (battery charge management)	-	0	1	1
Set-point temperature	°C	19	22	1
Set-back temperature	°C	15	19	1
Set-back start time	h	19	23	1
Set-point start time	h	5	8	1

3. RESULTS

The results of the calculations are shown in Figure 5, where each point represents a simulation run. The energy consumption and the PV production are normalized with respect to the building floor area. Obviously, all the results lie in the lower left triangular part of the diagram (below the bisector line) because self-consumption of PV generated power cannot be higher than total energy use. As can be expected, the optimal solutions (i.e the Pareto front) are, for the most part, found close to the border of the solutions domain (see Figure 6 and 7). It is immediately clear that some engineering judgment should be applied when evaluating such optimal solutions. In fact, in this preliminary application, the multi-objective optimization of total energy use, PV energy self-consumption and PV energy surplus are pursued with the same weight. From a practical point of view, the most interesting solutions are possibly the ones that ensure low total energy consumption (around 5 kWh m^{-2}), and, at the same time, high PV self-consumption (around 3-4 kWh m^{-2}). These can be found on the lower left part of the graphs. Looking at the "optimal" values assigned to the adjustable parameters for the points some results are obvious, for example the best results are obtained for higher values of the COP (HP rated COP = 4-5) and for operation of the batteries in parallel with the grid (*battery charge management* = 0). A bit more remarkable are the results obtained for the selection of the optimal value for some other parameters such as the capacity of the hot water storage tank (Figure 6) installed in the hydronic heating system and the total capacity of the installed batteries (Figure 7). As can be clearly inferred looking at the color of the dots in figures 6 and 7, the optimal combination of water and electricity storage is noticeably affected by the characteristics of the building. The buildings with the larger value of S/V = 0.63 seem to perform better with larger tanks and smaller batteries capacity with respect to the ones with smaller S/V = 0.3. This is probably due to the higher heat demand of the building that causes a high number of charge/discharge of the storage tank. On the contrary, in S/V=0.3 the storage tank should be smaller in order to decrease the residence time of energy in the storage tank and thus the heat losses.

4. CONCLUSIONS

The HVAC system of a building is becoming more and more complex in order to decrease energy use, increase the renewable energy quota exploited to cover such energy needs and, more recently, to maximize the self-consumption of in-situ generated renewable energy. In order to reach these targets, the role of local energy storage is becoming of fundamental importance. Such energy storage can be pursued at the building level with different methods: thermal energy can be stored exploiting the thermal capacity of the building structure and/or water storage tanks and electric energy using batteries. And it is quite possible that a balanced combination of these methods is the optimal solution. All this is making the task of the HVAC designer increasingly complex and the dynamic interaction among building, energy systems and occupant behavior should be taken into account especially in high performance buildings. The multi-objective optimization approach presented here can be a useful tool in order to steer the predesign and early design phase of a high performance HVAC system. Some preliminary results obtained with this approach are presented here for the heating system of a small building. The study points out the issues of coupling systems with high response time in high performance buildings. The optimal mix of HVAC configurations and managements are strictly related to the building characteristics. The buildings with low dispersing surface (S/V 0.30) and with South oriented windows required a higher battery capacitance, since the PV production is concurrence with the high solar gains and thus with the minimum in heating demand. Moreover, the low heating demand guides to the choice of small storage tank in order to limit the energy waste trough heat losses. On the other hand, the increasing dispersing surface (S/V 0.63) and the East oriented glazings ensure a high number of cycle of charge/discharge of the storage tank, allowing a reduction of the heat losses hence bigger storage thanks can be adopted. The authors recognize that there are still some shortcomings and are currently performing further research work in order to: a) shorten the computing time (now several hours of computer time are required to complete the run for each building) by means of high efficiency algorithms, b) investigate the effectiveness of the MOO objectives (to favor the solutions having lower total energy needs) and c) extend the application to a much larger variety of buildings having different size and structural characteristics and climates.

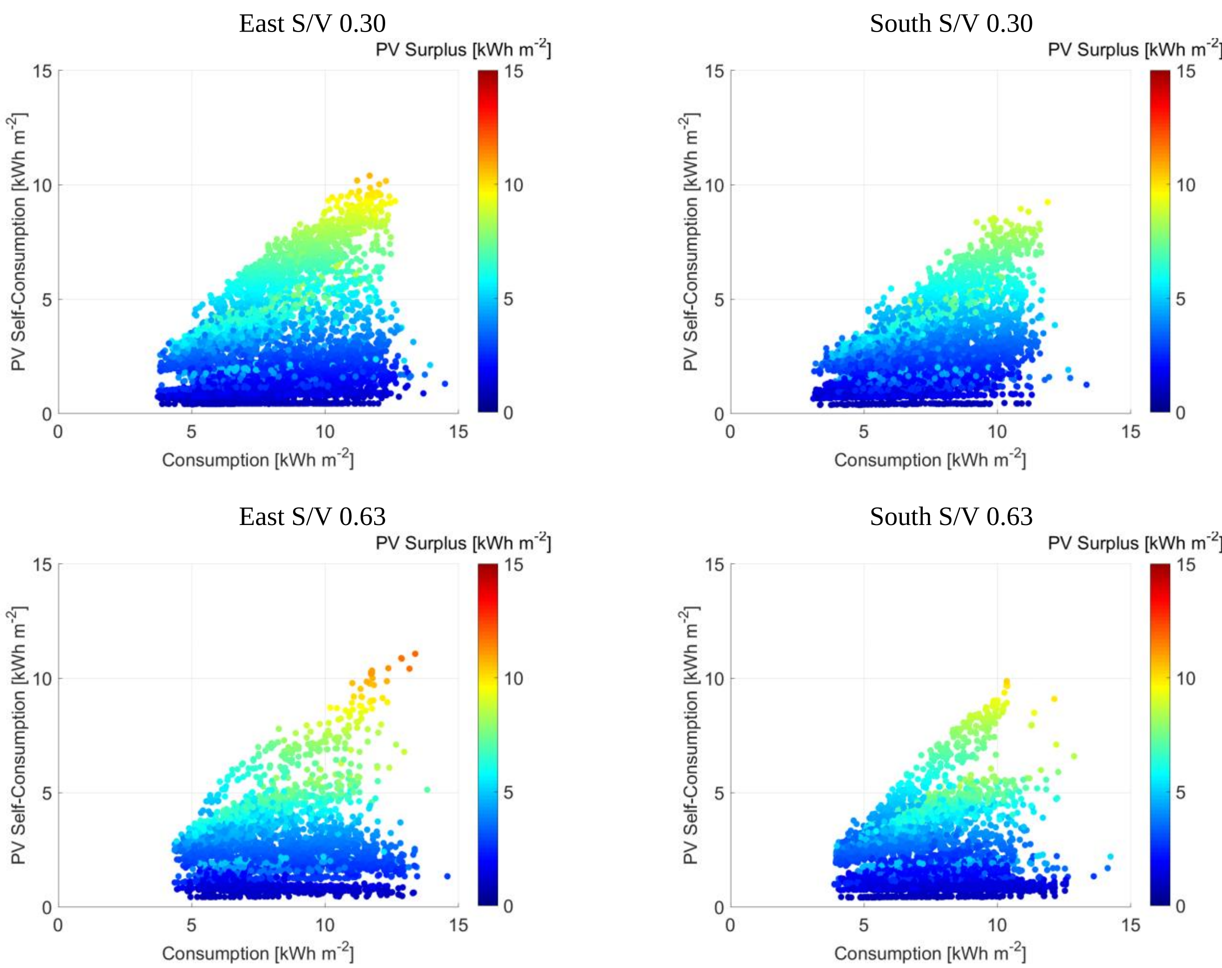
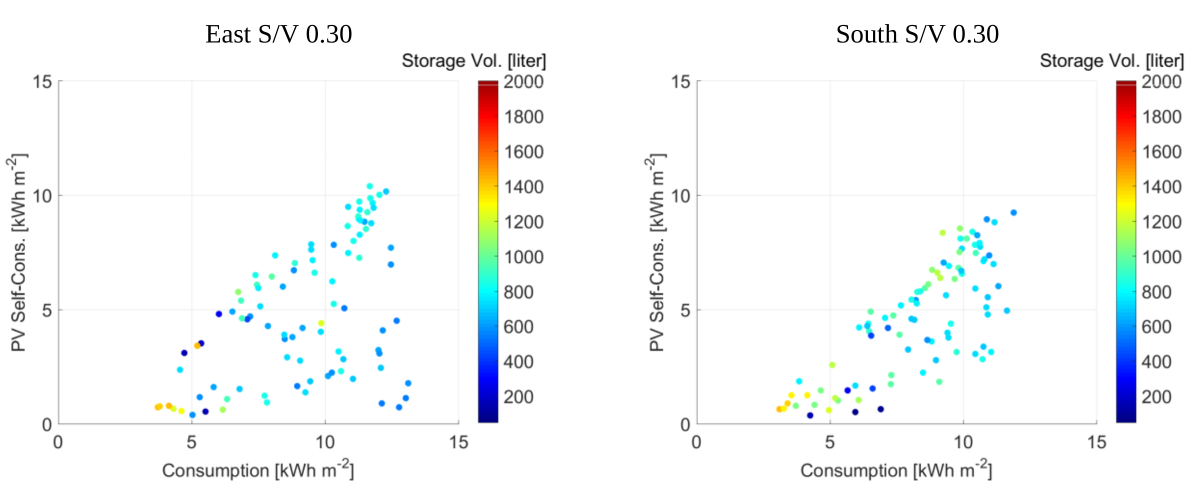


Figure 5: Objective functions for all the explored simulation field and for the four test cases. Each dot represents one of the simulation runs and together they show the spanned solution space. The colored scale shows the surplus energy generated by the photovoltaic (PV) panels delivered to the grid (i.e. the third MOO target parameter)



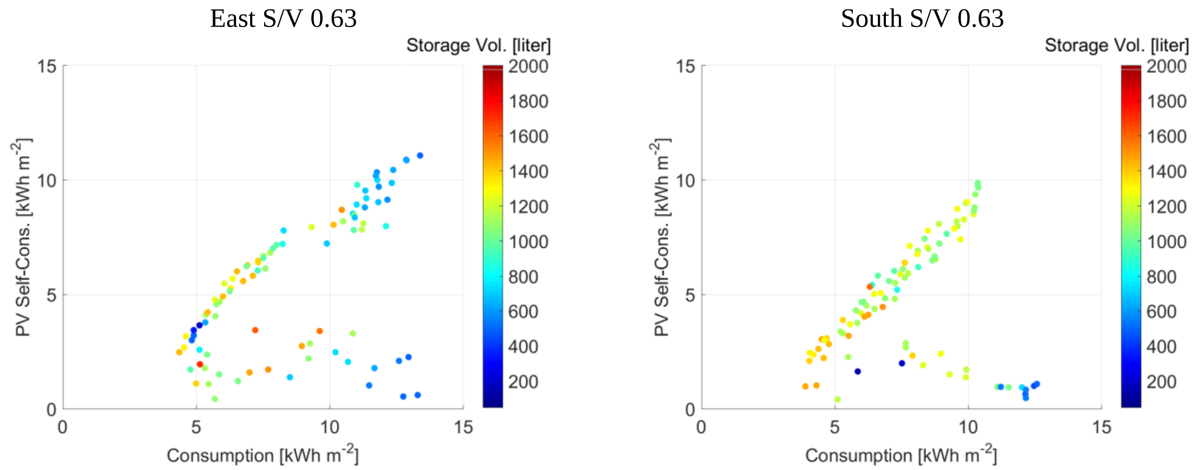


Figure 6: Pareto front points. Each dot represents one optimal solution in some sense. As explained in the text, the "really" optimal solutions are represented by the dots close to the 5 kWh m^{-2} energy consumption and 3-4 kWh m^{-2} PV generated energy consumption values. The colored scale shows the capacity (in liters) of the hot water storage tank installed in the hydronic heating system, calculated by the optimization process for each different solution.

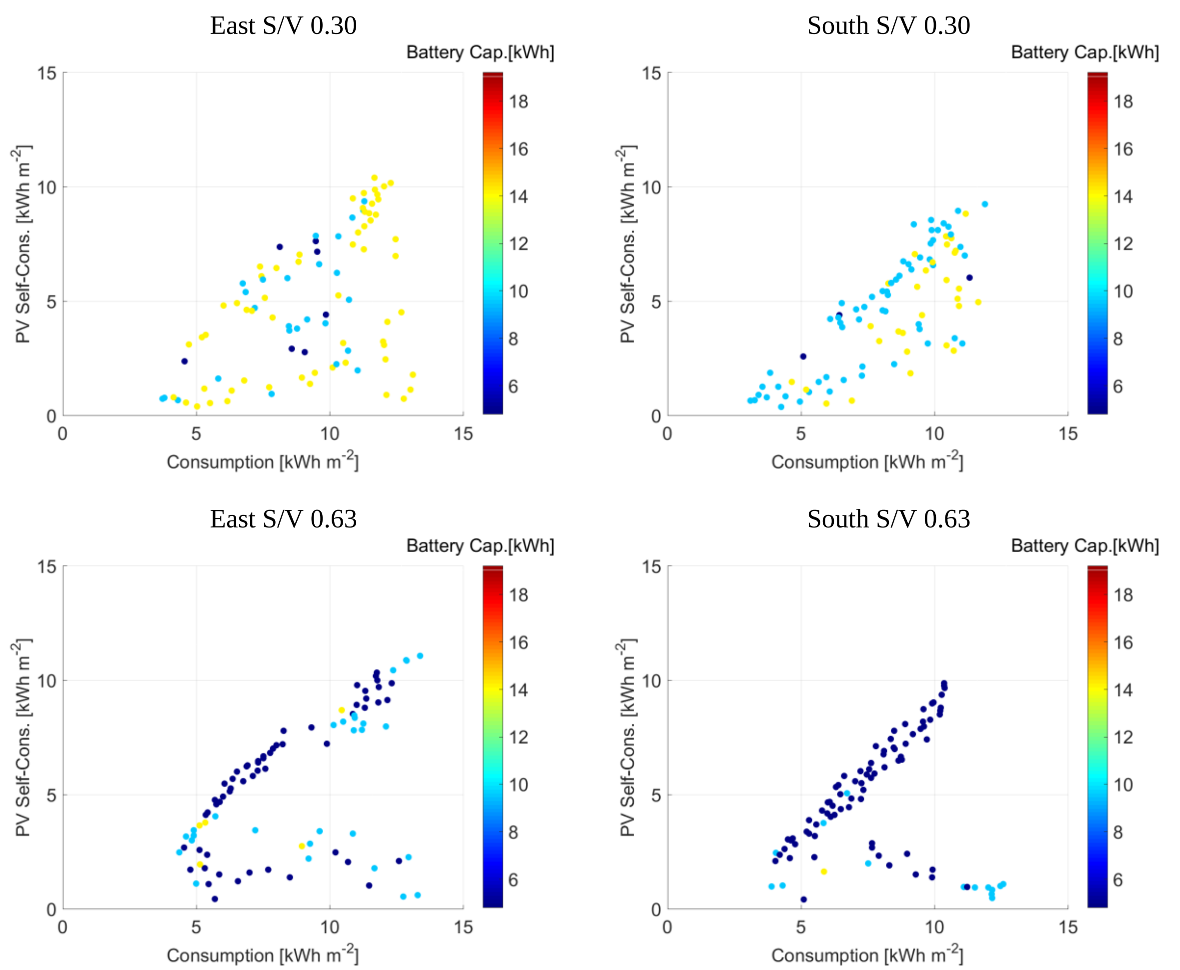


Figure 7: Pareto front points. Each dot represents one optimal solution in some sense. As explained in the text, the "really" optimal solutions are represented by the dots close to the 5 kWh m^{-2} energy consumption and 3-4 kWh m^{-2} PV generated energy consumption values. The colored scale shows the total capacity of the installed batteries (in kWh), calculated by the optimization process for each different solution.

NOMENCLATURE

COP	coefficient of performance	(–)
CR	capacity ratio	(–)
FSOC	fractional state of charge	(–)
f_{corr}	correction function	(–)

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