Multi-objective design optimization of a hybrid renewable energy system

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Abstract - A photovoltaic-thermal (PVT) collector is a solar-based micro-cogeneration system which generates simultaneously heat and power for buildings. Thermal and electrical energy storages are coupled with the PVT collectors to support fluctuating energy production in order to meet a certain energy demand. To maximize the self-consumption of renewable energy sources, the optimal size of the hybrid energy system components has to be determined. In this paper, a solar energy system is modelled and a genetic algorithm (NSGA-II) is used to obtain a Pareto front of optimal design solutions for decision makers.

Keywords: renewable energy, photovoltaic-thermal, micro cogeneration, multi-objective optimization, hybrid energy system

Nomenclature

A	area, m^2
C_B	battery capacity, kWh
c	specific heat, J/(kg K)
G	solar irradiation, W/m^2
h	heat transfer coefficient, $W/(m^2K)$
I	investment, (€)
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
NSGA	non-dominated sorting genetic algorithm
P	power, W
Q	heat flux, W
R	reliability
r_c	packing factor of collector
SOC	State-of-Charge
T	temperature, K
t	time, s
V	storage volume, m^3
Greek symbols	
η	efficiency
α	absorbance

$(\alpha\tau)$	effective absorbance
β	temperature coefficient; %/K
Index and exponent	
a	absorber
aux	auxiliary boiler
B	battery
CD	conduction
ch	charging
CV	convection
dis	discharging
e	environment
f	coolant fluid
g	glass cover
i	insulation
L	load
pv	photovoltaic
RD	radiation
t	tube bonding
TS	thermal storage

1. Introduction

The building sector has a high impact on greenhouse gas emissions and final energy consumption in the European Union (EU) by being the largest energy end-use sector with a share of 41% [1]. The micro combined heat and power (micro-CHP) units produce simultaneously heat and electricity from a single fuel source at high efficiency and close to the consumption point for building use. The units are referred up to 15 kW of electrical power [2]. The renewable energy based micro-CHP systems are in the key role in reaching the primary energy and pollutant emissions reduction targets of the EU [3].

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The photovoltaic-thermal (PVT) collector is a solar-based micro-cogeneration unit which produces electricity by the PV module and useful heat by cooling the PV module with a coolant fluid. This leads to increase overall system efficiency but also an increasing electrical efficiency due to the decreased operation temperature of the PV module [4]. Liang et al. [5] studied the performance of PVT collectors connected in series. They performed numerical and experimental study, in which 6 PVT collectors where connected in series resulting to total amount of 36 collectors. They analyzed coolant fluid outlet temperature, PV temperature, and electrical and thermal efficiencies. The serial connection of PVT collectors increases coolant outlet temperature until certain point but decreases the electrical efficiency of the last panels due to higher operation temperature. Buonomano et. al [6] performed a dynamic analysis of the hybrid energy system including PVT collectors, energy storages and electric vehicle. They studied energy, environmental and economic performance of the system powering a building. They also carried out a sensitivity analysis to optimize the system configuration.

The PVT collectors can be connected in series with multiple rows, and be integrated with electrical and thermal storages to provide energy for residential building use. The optimal size of the PVT system components depends mainly on the electrical and thermal energy demand of the building but also on the weather conditions and amount of solar radiation during the day. In order to maximize self-consumption of the solar system, the most of the produced energy has to be stored on-site for the later use of the building.

In recent years, the design methods have got alongside new design methods using nature inspired artificial intelligence methods, such as genetic algorithm (GA), evolutionary algorithm and particle swarm optimization (PSO). The objective function describes the key design criteria of the optimization problem. In many optimization cases, multiple objectives have to be satisfied in order to find a trade-off solution for the design. Due to this, instead of a single-objective optimization, the multi-objective optimization approach is recommended resulting in more accurate and realistic system design. [7]

In this given framework, a research contribution is provided by demonstrating multi-objective optimization of the PVT/battery/thermal storage system with the evolutionary NSGA-II approach. The objectives of the 3-dimensional optimization problem are to maximize the thermal and electrical reliability of the system and to minimize the initial investment costs. The Pareto optimal set of design solutions is derived and analyzed. The sensitivity analyze of the selected inputs is carried out.

2. Methodology

Photovoltaic-thermal (PVT) collectors provide low-grade heat for domestic hot water (DHW) production and electricity for building appliances. In this section, the model description of the hybrid renewable energy system in Fig. 3 including PVT collectors, thermal storage, battery system, thermal load and electrical load is presented. A residential building is selected to present the energy consumption side of the system. The hourly yearly meteorological data of Strasbourg, including global solar radiation, ambient temperature and wind speed, is used to simulate PVT collector thermal and electrical energy production. Strasbourg is located in the Central Europe in Northern France and has oceanic and semi-continental climate. The system is modelled into Matlab/Simulink environment and the open-source CARNOT Toolbox [8] is used to model the system components, such as thermal and electrical storages.

The solar system provides the energy demand of the building and an auxiliary boiler is used to support DHW production. The electricity production of the PVT collectors is supported by the electric grid connection and the surplus production is first stored to the battery system or sold to the grid.

2.1. PVT collectors

The dynamic model of the covered PVT collector have been presented in the literature [4,9–12] and used to evaluate the thermal and electrical performance of the collector. The following energy balance governing equations of various collector layers are used to model the single water-based flat plate PVT collector.

The glass cover (g):

$$m_g c_g \frac{dT_g}{dt} = h_{g-e,CV}A\left(T_e - T_g\right) + h_{g-e,RD}A\left(T_{sky} - T_g\right) + h_{g-pv,CV}A\left(T_{pv} - T_g\right) + h_{g-pv,RD}A\left(T_{pv} - T_g\right) + A\alpha_g G_{irr} \tag{1}$$

The PV layer (pv):

$$m_{pv} c_{pv} \frac{dT_{pv}}{dt} = h_{g-pv,CV}A\left(T_g - T_{pv}\right) + h_{pv-g,RD}A\left(T_g - T_{pv}\right) + h_{pv-a,CD}A_{pv-a}\left(T_a - T_{pv}\right) + h_{pv-t,CD}A_{pv-t}\left(T_t - T_{pv}\right) + G_{irr}A_{pv}(\alpha\tau)_{pv} - G_{irr}Ar_c\eta_{EL(T)} \tag{2}$$

In which electrical efficiency $\eta_{pv(T)}$ depends on the photovoltaic cell/absorber layer temperature T_{pv}. Due to this the electrical efficiency of the PV depends linearly on the temperature T_{pv}, the temperature coefficient β_{pv} and on the efficiency at standard conditions T_{ref}. The efficiency is calculated according to the following relation:

$$\eta_{EL(T)} = \eta_{STC}\left[1 - \beta_{pv}\left(T_{pv} - T_{ref}\right)\right] \tag{3}$$

The absorber layer (a):

$$m_a c_a \frac{dT_a}{dt} = h_{a-pv,CD}A_a\left(T_{pv} - T_a\right) + h_{a-t}A_{a-t}(T_t - T_a) + h_{a-i,CD}A_{a-i}(T_i - T_a) \tag{4}$$

The tube bonding (t):

$$m_t c_t \frac{dT_t}{dt} = h_{t-pv,CD}A_{pv-t}\left(T_{pv} - T_t\right) + h_{t-a}A_{a-t}(T_a - T_t) + h_{t-i,CD}A_{t-i}(T_i - T_t) + h_{t-f}A_{t-f}(T_f - T_t) \tag{5}$$

The insulation layer (i):

$$m_i c_i \frac{dT_i}{dt} = h_{a-i,CD}A_{a-i}(T_a - T_i) + h_{t-i,CD}A_{t-i}(T_t - T_i) + h_{i-e,CD+CV}A(T_e - T_i) \tag{6}$$

The coolant fluid (f):

$$m_f c_f \frac{dT_f}{dt} = h_{t-f}A_{t-f}\left(T_a - T_f\right) + \dot{m}c_f\left(T_{f,in} - T_{f,out}\right) \tag{7}$$

The governing equations (1-7) are implemented to the Matlab/Simulink. The more detailed description of the equations and model validation are presented in the Author's previous work [10]. The model of the single PVT collector is used to model the PVT field with the number of PVT collectors in series N and the number of PVT rows M.

2.2. Electrical storage

The battery system is used to store produced electricity when the electricity demand of the building is lower than the production from the PVT collectors. The use of battery storage improves the matching between the electricity production and demand in order to maximize the self-consumption.

The battery model is based on the load balance between the electricity production and demand. If the electricity production is higher than demand, the battery is charged and discharged if the demand is higher. If the battery is full and the demand is low, the electricity is sold to the grid.

$$P_{load}(t) = P_{PVT}(t) + SOC_B(t)P_{dis} \tag{8}$$

where SOC_B is the battery state of charge.

$$SOC_B(t) = SOC(t - \Delta t) + \frac{\eta_B P_{ch}(t)\Delta t}{C_B} - \frac{P_{dis}(t)\Delta t}{C_B} \tag{9}$$

where P_{ch} and P_{dis} are charging and discharging powers and C_B is the battery capacity. The battery block of the CARNOT Toolbox is used to simulate the battery behavior.

2.3. Thermal storage

The considered solar energy system includes a stratified thermal storage for hot water to improve the system efficiency and enable the matching between the heat production and demand. The CARNOT Toolbox was used to model the stratified thermal storage of the system. The volume of the storage is divided into nodes to present the stratification. For each node, the energy balance is calculated in order to find the current temperature of each node. This modelling approach is widely used in the literature [13,14]. The CARNOT tank model called "Storage_Type_1" was used in the simulation. The model present a heat buffer with 4 nodes in which solar heat is injected and transferred to the cold DHW flow by heat exchangers. More detailed description of the tank model is presented in [8].

2.4. Energy demand profiles

The residential building is selected to present the demand side of the model in the optimization problem. The normalized standard electricity demand profiles generated by German Association of Energy and Water Industries, BDEW (Bundesverband der Energie- und Wasserwirtschaft) [15] are used to simulate electricity demand in every 15 min in the residential building. The profile is based on the measured data and takes into account electrical appliances excluding special applications, such as heat pumps and electrical storage heaters. The used electricity profile includes 3 different time periods of the year: winter, summer and transition. Additionally, 3 different day types are presented: work day, Saturday and Sunday/holiday.

In addition to the electricity demand, the system is used to produce domestic hot water (DHW). The household is assumed to include 4 inhabitants and daily DHW demand profile is used according to [16].

2.5. Multi-objective optimization

In this study, the Matlab function called gamultiobj of the Global Optimization Toolbox is used to run the multi-objective design optimization of the renewable energy system. The gamultiobj-function creates a set of optimal solutions in the space of decision variables on the Pareto front. The function uses a controlled, elitist genetic algorithm, which is a variant of NSGA-II. The detailed description of the algorithm is presented by Deb in [17]. Generally, the multi-objective optimization problem of two or more conflicting objectives is described mathematically as follows [4]:

Minimized/Maximized $f_m(x)$, $m = 1, 2, \ldots, M$;

Subject to $g_j(x) \geqslant 0$, $j = 1, 2, \cdots, J$;

$h_k(x) = 0$, $k = 1, 2, \ldots, K$;

$x_i(L) \leqslant x \leqslant x_i^{(U)}$, $i = 1, 2, \cdots, n$;

In this formulation, the objective functions are minimized or maximized subject to certain constraints.

The flow chart of the NSGA-II optimization process is presented in Fig. 1. First, the objective functions and optimization variables are defined for the optimization problem. The initial population (the parent population) and score matrices for all decision variables are created with the simulation model of the system and based on the input data and bounds of the decision variables. Next, the created matrices are given for the gamultiobj-function, which starts the iterative process by evaluating the fitness function with the simulation model and making selection, crossover and mutation of the population in order to generate a better generation of the population [10].

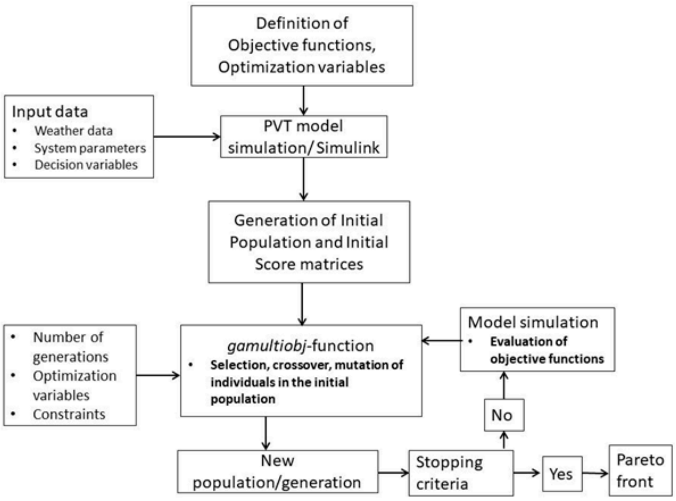

Figure 1: *The simulation-based multi-objective optimization process. [10]*

In this study, the electrical and thermal reliability of the system and the initial investment costs are three objectives to be optimized. The goal of the optimization is to find a Pareto optimal set of system designs to maximize self-consumption and autonomy of the system over year with the minimum initial investment costs. The 3-dimensional optimization problem of the system design is formulated as follows. To minimize:

$$f_1(x) = \frac{\sum_t^{8760} Q_{aux}(t)}{\sum_t^{8760} Q_{DHW}(t)} = \frac{\sum_t^{8760} m_L(t) c_p \left(T_{set}(t) - T_{top}(t)\right)}{\sum_t^{8760} Q_{DHW}(t)} = R_{thermal} \tag{10}$$

$$f_2(x) = \frac{\sum_t^{8760} \left[P_L(t) - \left(P_{PVT}(t) + SOC_B(t)\right)\right]}{\sum_t^{8760} P_L(t)} = R_{electric} \tag{11}$$

$$f_3(x) = I_{PVT} A + I_B C_B + I_{TS} V_{TS} = I_{total} \tag{12}$$

Where $R_{electric}$ and $R_{thermal}$ are the electrical and thermal reliability of the system, respectively. The reliability shows the share of the load that cannot be met by the solar system. I_{total} is the total initial investment of the system including the initial investment costs of PVT collectors (I_{PVT}), battery system (I_B) and thermal storage (I_{TS}). SOC_B, P_L and P_{PVT} represent battery power, electrical power of load and PVT generation, respectively. Q_{aux}, Q_{DHW}, m_L, T_{set} and T_{top} are the generated thermal power by auxiliary device, required thermal power of DHW, DHW demand, the required temperature of DHW and temperature of water in the top of heat storage, respectively. Table 1 presents the selected decision variables of the system to be optimized by minimizing the objective functions. Table 2 present the estimated prices of the system components used in the optimization.

	Decision variable	Bounds	Unit
$\dot{m}$	Coolant mass flow	$0.022 \leq x(1) \leq 0.024$	kg/s
N	Nr. of PVT in series	$1 \leq x(2) \leq 6$	-
M	Nr. of PVT in rows	$1 \leq x(3) \leq 5$	-
C_{bat}	Battery capacity	$4 \leq x(4) \leq 10$	kWh
V_{TS}	Thermal storage volume	$0.1 \leq x(5) \leq 0.4$	m^3

Table 1: *Decision variables for multi-objective optimization problem.*

Component	Price	Ref.
PVT collector	325 €/m^2	DualSun company
Thermal storage	2.95 €/m^3	[13]
Electrical storage	1143 €/kWh	Enphase company

Table 2: *The component prices of the system*

3. Results and discussion

The yearly electricity and DHW demand profiles of the residential building with 4 inhabitants were used to perform the multi-objective optimal component sizing optimization of the hybrid energy system including PVT collectors, thermal storage and battery system with the NSGA-II algorithm. The hourly yearly meteorological data of Strasbourg was used to simulate PVT collector thermal and electrical energy production. As a result the Pareto front was obtained for the optimization problem and is presented in Fig. 2.

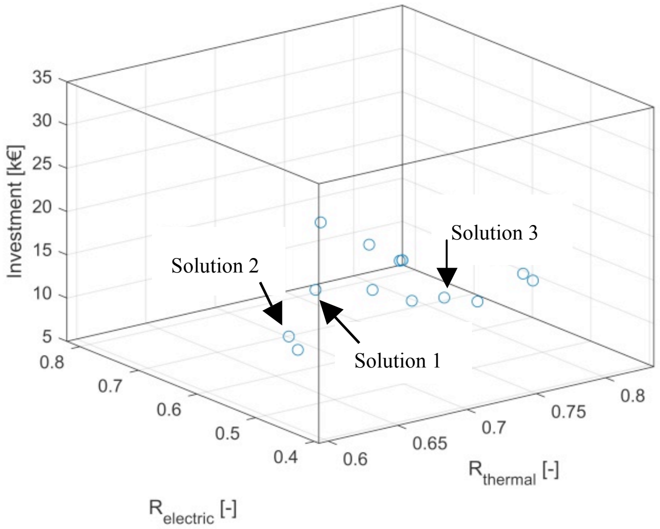

Figure 2: *The Pareto front in the objective space*

The goal of the optimization was to maximize self-consumption and autonomy of the system over year with the minimum initial investment costs. The optimization algorithm found 14 non-dominating optimal solutions for the component sizing of the hybrid energy system. The solutions are presented in Fig. 2. Within the optimal solutions, the yearly thermal reliability $R_{thermal}$ was between 0.83 and 0.59. On the other words, at least 59% of the yearly thermal energy demand had to be covered by an auxiliary boiler and 41% is covered by the PVT collectors. At the same time, the yearly electrical reliability $R_{electric}$ was between 0.82 and 0.39, and at least 39% of the yearly electricity demand had to be bought from the electric grid. The initial investment costs of the optimal solutions were between 5517 € and 30 480 €. However, the best reliability of the system was reached with the investment costs of 22 600 € including 3 PVT collectors in series and 5 rows, the battery capacity of 9.5 kWh and thermal storage volume of 0.4 m^3.

The Pareto front presents the optimal set of solutions in the objective space and can be used by the decision-makers to select the most reasonable solution for each application. Table 3 presents 3 solutions with different range of investment costs selected from the Pareto front.

	PVT in series	PVT rows	C_B (kWh)	V_{TS} (m^3)	R_{th}	R_{el}	Inv. (€)
Sol. 1	3	5	9.5	0.4	0.59	0.40	22601
Sol. 2	1	3	7.3	0.3	0.64	0.55	11244
Sol. 3	1	2	4.7	0.1	0.80	0.66	7061

Table 3: *The selected solutions of the Pareto front*

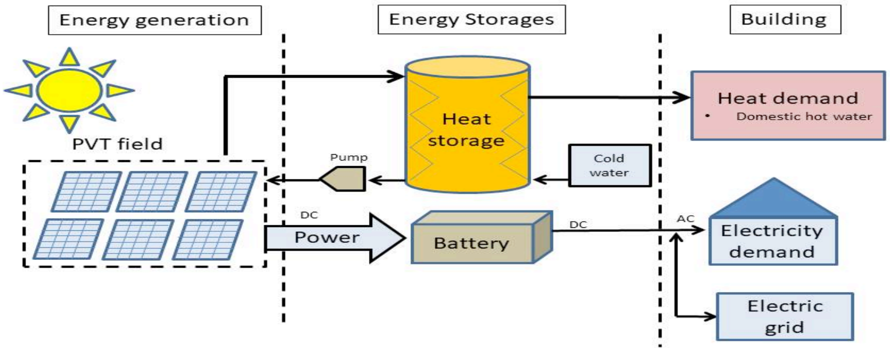

Figure 3: *The system layout of the hybrid renewable energy system.*

4. Conclusion

In this paper, a PVT/battery/thermal storage hybrid energy system was modelled into Matlab/Simulink environment and the optimal sizing problem was solved using NSGA-II algorithm. The system was optimized for a residential building electricity and DHW demand, and the weather conditions of Strasbourg, were used to estimate PVT energy production.

The main objective of the optimization was to maximize self-consumption and autonomy of the system over year with the minimum initial investment costs. The objective functions were to minimize thermal and electrical reliability, and the initial investment costs. The Pareto front was obtained containing a set of the optimal solutions within the objective space. Within the Pareto front, the higher investment costs resulted in the better reliability of the system. The results revealed that the studied energy system cannot cover all energy demand under defined constraints but an additional energy source is required and the considered energy system should be extended to be a hybrid renewable energy system that integrates different energy conversion and storage technologies in order to form a sustainable and energy efficient set-up to satisfy a certain energy demand. The optimization results revealed that the multi-objective optimization with the genetic algorithm is suitable for the hybrid energy system optimal component sizing problem.

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