ECO-ENERGETIC ANALYSIS AND SIZING OF CHP/PV ENERGY SYSTEM IN RESIDENTIAL APPLICATION

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ABSTRACT

Economic, energetic and environmental concerns foster the development of clean and efficient solutions for residential energy systems. Combined heat and power (CHP) systems allow covering the heat and electricity demand simultaneously. Micro-CHP systems are expected to spread in building application during next years. Thus, finding an optimal size and configuration between micro-CHP, PV module and battery could help to improve the energy saving potential of such systems.

The goal of the study is to identify and understand the influence of some key parameters like PV size, CHP power or battery size on CHP/PV system eco-energetic profitability in residential application with focus on the interactions between components. A parametric study is performed to find an optimal trade-off between objective functions like electricity self-sufficiency, electricity self-usage, CO_2 impact or costs. The heating system of the building is modelled and simulated in a Simulink/Carnot model and analysed. The system is composed of a micro-CHP plant (Var.I: 2.3 kW_{th} / 1 kW_{el} ; Var.II: 9 kW_{th} / 5 kW_{el}), a gas fired burner (19 kW_{th}), a PV system (dif. sizes: 0-10 kW_p), a battery bank (dif. sizes: 0-10 kWh) and a thermal storage. Two buildings were evaluated, a new built (45 $kWh/m^2/a$) and an existing non-retrofitted (150 $kWh/m^2/a$). The control strategy is primarily designed to satisfy the heat demand of space heating and DHW.

For both buildings, a configuration was found with a very low need for grid electricity (< 20 kWh/a). Nevertheless, this configuration does not correspond to the best solution from an economical point of view. Therefore, a trade-off solution is proposed to minimize the annual costs and the electricity imported from grid. As example, for the retrofitted building, a 10 kW_p PV system and a 2.5 kWh battery gives an annual cost of 2'280 CHF with a grid electricity import of 198 kWh/a.

Keywords: Micro-CHP, Residential energy system, Photovoltaic, Battery storage

INTRODUCTION

CHPs are very efficient systems able to cover the heat and electricity demand of buildings. By coupling PV modules and CHP, the electricity demand, on an annual basis, is easily covered. Nevertheless, to cover the entire electricity demand, particularly during the night (no PV production), a battery system is needed to store the electricity produced during the day and to restore it, when needed. Having a building which is completely autonomous can also be interesting from an economical point of view. Indeed, the electricity selling price is expected to drop while the buying price will increase. Thus, it is interesting to maximize the amount of electricity produced on site and to minimize the importation. In this study, it is tried to identify the influence of parameters like PV size and battery size on CHP/PV system eco-energetic performance. Additionally, the existence of an optimal configuration, between costs and electricity self-sufficiency is evaluated. The environmental impact is also highlighted using the CO_2 emissions as indicator.

METHOD

This study is simulated dynamically in Matlab/Simulink using the Carnot Blockset. The energy system consists of a CHP, a backup gas boiler, a PV installation and a battery bank. The produced heat is stored in a 750 l tank, from which heat is taken for the space heating and the DHW. The buildings are based on the SFH45 from the IEA HPP Annex 38 / SHC Task 44 "Solar and heat pump systems" (A38T44) [1] and are located in Strasbourg (moderate climate).

Building model

The first building (B1) represents a newly built single-family house with a good thermal envelope. Its space heating demand is 45 kWh/m^2/a. The second building (B2) represents an existing non-retrofitted building with a space heating demand of 150 kWh/m^2/a. Both buildings have an energy reference area of 150 m^2. Figure 1 depicts the schematic of the building energy system. Some conditions and parameters are applied for all simulations:

- The hot water tapping profile was simplified to three tapings per day (7:00 / 80 l; 12:00 / 40 l; 19:00 / 80 l) corresponding to a total need of 200 l/day at 45°C (2'970 kWh/a).
- The heat is generated by the CHP (and the backup heater) and stored in a 750 l tank, which serves for the DHW and for the space heating.
- The electricity demand profile was generated with the tool Load Profile Generator® [2]. It represents a typical usage of households (kitchen, multimedia, lighting,…), where two adults and two children are living. This represents an annual consumption of 3'247 kWh.
- Two types of internal heat gains are considered in the simulations. One occupation profile corresponding to a yearly value of 1'350 kWh and a waste heat profile from electrical equipment corresponding to a yearly value of 2'010 kWh. Both profiles are taken from the building definition in IEA HPP Annex 38 / SHC Task 44 [1].
- For all cases, the PV panels are south oriented with an angle of 20° from horizontal.
- For the space heating, the heat delivery system is a floor heating (35°C) and a radiator (60°C) for the building B1 and B2 respectively.
- A natural gas burner of 19 kW, with an efficiency of 98%, is used as backup heater.
- The battery is modelled like an integrator with a charging/discharging efficiency of 95% (roundcycle efficiency of 90%). A power limitation of 4kW is applied. No self-discharge rate is considered.
- The CHPs are modelled in a simplified way, taking into account the total gas consumption and the efficiencies to evaluate the heat and the electricity generated.
- For the electricity self-usage, the CHP electricity has always the priority over PV when CHP and PV are producing at the same time.
- The CHP and backup burner control strategy is only based on the heat needs. The tank temperature is maintained at the desired level (with a hysteresis) during the entire year.

Energetic analysis

Two indicators are used to evaluate the energetic performances, the electricity taken from or fed to the grid. It represents on one side, the level of electricity self-sufficiency of the building and on the other side, the part of electricity produced and not used on-site.

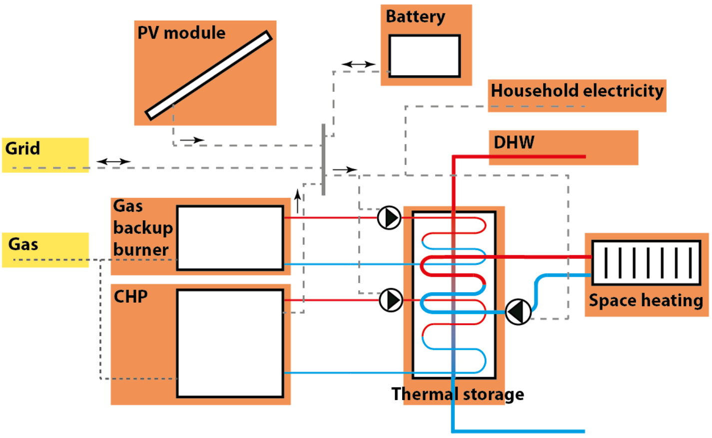

Figure 1: Schematic of the energy system

Economic analysis

The following components are considered for the investment: PV system, battery bank, micro-CHP and backup heater. The currency chosen is the Swiss Franc (the inflation was not considered). At the time of the study the currency change CHF-EUR was 1.03 CHF/EUR. The parameters used for the investment cost calculation are recapitulated in Table 1. For the PV system, the Swiss government offers a contribution of 1'400 CHF + 680 CHF/kW$_p$ to foster the installation of PV modules (new installation built between 04.2015 and 09.2015). All components have a lifetime of 20 years except the battery, for which the lifetime is only 10 years. Thus, the battery is replaced once during the entire lifespan. The economic indicator used in this study is the annual cost (CHF/a). It is composed of the operation costs and of the annualized investment, assuming that this investment is a loan repaid over the entire lifespan (20 years with an interest rate of 6%).

Category	Value	Source
PV system (incl. inverter)	1.08·(1.56 EUR/W$_p$)	Hoppmann et al. [3]
Battery bank	1.08·(171 EUR/kWh+242 EUR/kW) (lead-acid)	Hoppmann et al. [3]
Micro-CHP	3'400 EUR/kW$_{el}$	Brandoni et al. [5]
Backup heater	115 EUR/kW	Kapsalaki et al. [6]

Table 1: Economic parameter for investment cost calculation

Category	Value	Source
PV system (maintenance)	1.5% of PV costs per year	Hoppmann et al. [3]
Battery bank (maintenance)	19 EUR/kW per year	Hoppmann et al. [3]
Micro-CHP (maintenance)	0.021 EUR/kWh$_{el}$	Brandoni et al. [5]
Backup heater (maintenance)	80 EUR per year	Tronchin et al. [7]
Gas price	0.1031 CHF/kWh	IPC / energy [8]
Electricity buying price	0.2149 CHF/kWh	IPC / energy [8]
Electricity selling price	0.1455 CHF/kWh	Groupe E [9]

Table 2: Economic parameter for operation costs calculation

The operation and maintenance costs are presented in Table 2. The electricity and gas prices are taken from the actual Swiss market. In this study, the electricity and gas prices were considered constant over the 20 years lifespan.

Environmental analysis

The environmental analysis is based on the energy system CO_2 emissions. For the electricity, based on the Swiss mix, the CO_2 specific emission of 0.091 kg/kWh is taken from the information given by the "Federal Office for the Environment" [10]. For the gas amount consumed a specific emission of 0.202 kg/kWh is also considered [11].

Decision variables

For the analysis, some parameters are changed to see their influences on the eco-energetic performances:

- The PV panel peak power is varied between: 0 kW - 2.5 kW - 5 kW - 7.5 kW - 10 kW.
- The battery capacity is varied between: 0 kWh - 2.5 kWh - 5 kWh - 7.5 kWh - 10 kWh.
- Two different micro-CHPs are evaluated. The first one (CHP1) has an electric power of 1 kW_{el} and a thermal power of $2.33kW_{th}$ with efficiencies of 0.27 and 0.63 respectively. The second one (CHP2) has an electric power of 5 kW_{el} and a thermal power of 9 kW_{th} with efficiencies of 0.33 and 0.6 respectively.

RESULTS AND DISCUSSIONS

The results are presented in Table 3. The solution with the lowest investment cost is presented as reference. For each indicator, the best solution is presented with the corresponding value of the decision variables. An additional trade-off point is presented, which is defined as follow: minimal annual cost possible with a maximal electricity import of 200 kWh/a (about 10% of import without PV and battery).

Some general comments can be made:

- All configurations have a positive annual electrical balance.
- Heat demand of the building is always covered, including domestic hot water.
- For all cases, the reduction of CO_2 emissions is relatively low (-3%).
- Since the priority is made on the electricity produced by the CHP, the PV electricity is mainly fed to the grid (60-90%). For the CHP, the part being fed to the grid varies between 40 and 55%.
- The degree of electricity self-sufficiency reaches quickly 90% with a battery. The battery bank has the biggest impact than the PV size. It works mainly as a daily storage.
- PV modules size has an important effect on operating costs since the overproduction is sold to the grid.
- Since the electricity can be exported and sold to the grid, the operation costs decrease quickly with the PV size: about 50% reductions when having a 10 kW_p PV system compared to no PV system.
- As reference, for building B2, if all electricity was bought and all heat produced by the gas burner, the annual cost would be 3'630 CHF/a (investment included).
- It can be seen that for both buildings, the small CHP (CHP1) has better performances. It has lower costs and the peak power heat demand is covered by the backup gas burner.

For the building B1, the configuration with the lowest amount of electricity taken from the grid is the one with a 10 kW_p PV system and a 10 kWh battery. In this case, the building is almost autonomous, only 16 kWh are imported per year, which are mainly due to maximum peak power demand. This is also the solution with the lowest CO_2 emissions. For the lowest annual cost, the configuration is a 10 kW_p PV system and no battery. The total costs are 2'060 CHF/a. It corresponds to the solutions with the biggest electricity export. The tradeoff point was found with an electricity importation of 198 kWh and an annual cost of 2'280 CHF. With

10 kW$_p$ PV, it can be seen that already a small battery (2.5 kWh) can reduce the amount of grid electricity the import considerably (from 1'130 to 198 kWh). Figure 2 shows the imported electricity and the annual costs for the building B1 with the CHP1. Without PV system, the imported amount of electricity is already reduced by about 75% with a 2.5 kWh battery. For the trade-off point of building B1, 50% of the initial investment is the PV system. The CHP represents 20% and the battery bank 17%.

		LIC	**LGI**	**LCO2**	**LYC**	**TO**
New building B1	CHP model	CHP1	CHP1	CHP1	CHP1	CHP1
	PV size [kW$_p$]	0	10	10	10	10
	Battery size [kWh]	0	10	10	0	2.5
	Grid import [kWh/a]	2'030	16	16	1'130	198
	Grid export [kWh/a]	2'720	10'000	10'000	11'230	10'200
	CO$_2$ emissions [kg/a]	3'620	3'430	3'430	3'530	3'450
	Annual costs [CHF/a]	2'560	2'520	2'520	2'060	2'280
Existing building B2	CHP model	CHP1	CHP1	CHP1	CHP1	CHP1
	PV size [kW$_p$]	0	10	10	10	10
	Battery size [kWh]	0	10	10	0	2.5
	Grid import [kWh/a]	1'780	14	14	950	110
	Grid export [kWh/a]	3'500	11'050	11'050	12'100	11'160
	CO$_2$ emissions [kg/a]	7'080	6'920	6'920	7'010	6'930
	Annual costs [CHF/a]	4'190	4'170	4'170	3'710	3'930

Table 3: Indicators and decision criteria for each scenario (LIC: lowest investment costs / LGI: lowest grid import / LCO2: lowest CO2 emissions / LYC: lowest annual cost / TO: trade-off point)

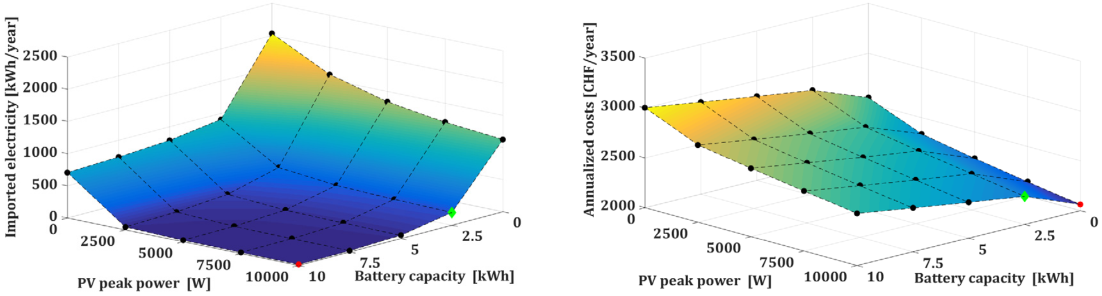

Figure 2: Imported electricity and annualized costs for building B1 with CHP1 (diamond/green point: TO point)

For building B2, the lowest grid import solution corresponds also to a 10 kW$_p$ PV system and a 10 kWh battery. The configuration giving the lowest annual cost is a 10 kW$_p$ PV system without battery. It gives an annual cost of 3'710 CHF. In comparison, for the same building but all the electricity imported and all the heat produced from the gas burner, the annual cost would be 3'630 CHF (investment of gas burner included). Once again, a big PV system allows selling a lot of electricity (up to 12'000 kWh/a), thus reducing the operating costs considerably (~30%). A good tradeoff solution is the one with a 10 kW$_p$ PV system and a small battery of 2.5 kWh. It allows to reduce the grid import to 110 kWh/a and to limit the yearly costs to 3'930 CHF.

A sensitivity analysis was made to evaluate the impact of the inputs like investment costs, maintenance costs or gas and electricity buying price. It turns out that the most influencing parameters are the PV investment costs, the gas buying price and the electricity selling price.

For example, for the trade-off point of building B1, the annual cost is increased by 23.4% when the PV investment cost is increased by 30% and by 23% when the gas price is increased by 30%, which shows the big impact of PV purchasing price and electricity selling price on an economic analysis over 20 years.

CONCLUSION

This study showed that a CHP/PV system combined with battery storage can clearly reduce the building dependency on the grid. It was found that a small battery (2.5 kWh) helps already to improve electricity self-sufficiency of the building (+30%) without increasing too much the annual cost (+10%). A bigger battery is not needed since the battery works as a daily storage and it would only increase the investment cost without reducing the operation cost or increasing considerably the level of self-sufficiency of the building. From a point of view of electricity imported, a big PV system (10 kW_p) is not needed but such an installation is profitable from an economic point of view since the electricity produced can be sold. For both buildings the small CHP seems to be more profitable. Both CHPs are able to cover correctly the needs but the high investment cost of the CHP2 yield to high annual costs. In this study, the regulation scheme was not optimized. A new control strategy based on both heat and electric demand could reduce the costs and the electricity importation or allow minimizing the gas consumption (depending on the objective function to minimize / maximize).

The electricity and gas prices were considered constant over the entire lifespan. It was shown in the sensitivity analysis that a modification of those costs in the future can have a big impact on the economic analysis and profitability. Thus the energetic indicator should be taken with more weight that the economic indicators in case of design decision.

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