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# A multi-objective optimization model for the operation of decentralized multi-energy systems

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**Abstract.** A multi-energy system couples several carriers such as electricity and heat to meet mutual synergies, optimizing the global efficiency of the system.

In this study, a multi-objective optimization is developed to establish the optimal design of a decentralized multi-energy system, by maximizing the renewable energy coverage rate and minimizing the operation costs at the same time. To retrace the typical demand profile that groups together the different uses of a neighbourhood, historical data are used in addition to simulation of buildings. On this basis, a set of energy production systems are modeled to form a multi-energy system providing energy to a neighbourhood in Nantes (France). An optimal sizing of the technologies is carried out using a genetic algorithm. Two objective functions are considered based on renewable energy coverage rate and operation/total cost. The study shows that renewable energy systems integration leads to higher total costs compared to a boiler only system, whereas when considering operation costs only, it is possible to reach a 12 % renewable energy system coverage rate and realize cost savings at the same time.

## 1. Introduction

In order to meet European and global targets to limit greenhouse gas emissions, a massive implementation of renewable energy systems (RES) is necessary. However, the large-scale integration of such RES is not trivial, due to intermittent production. To meet the demand, RES need to be combined with energy storage and controllable backups fueled by fossil resource.

Multi-energy systems (MES) whereby several energy carriers are strongly coupled, are promising opportunity to ensure high penetration of RES, thanks to the flexibility offered by the conversion from a carrier to another [1]. For example, [2] showed that an electricity-to-heat conversion can lead to an increase of 40 to 200 % of wind power penetration in Helsinki's energy network. Besides, energy savings can be target by exploiting the synergies of the carriers [3]. In that view, MES conversion and transformation have to be modeled, with the energy hubs concept [4, 5] or an energy flow analysis [6, 7, 8]. Then, mono-objective [6], multi-objective [7, 9] optimization or multicriteria decision aiding tools [8] are used to determine their optimal design [8, 6] and control [7].

In this paper, a multi-objective optimization is applied to determine the optimal combination of technologies of a MES which provides heat and power to a neighbourhood. Two objective functions are considered based on renewable energy coverage rate and total or operation cost. The problem will be described in section 2 while methodology and associated results will be show in section 3 and 4, leading to discussions and conclusion.



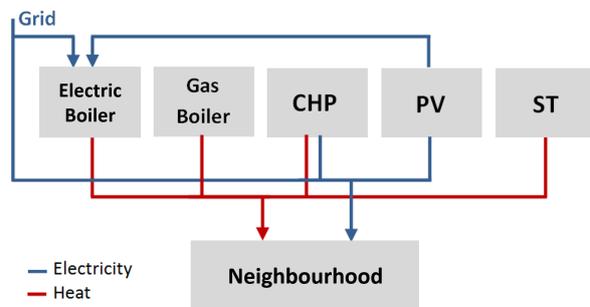
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## 2. Problem description

The case of study is a neighbourhood in the north of Nantes (France). It covers an area of 33.5 hectares including IMT Atlantique's campus and 45 single-family houses (Fig. 1). The aim is to find the MES optimal design to supply heat and electricity consumed by buildings. The considered system contains a Combined Heat and Power unit (CHP) composed of a gas turbine (GT) and a heat recuperation system (HRS), a gas boiler (GB), an electric boiler (EB), photovoltaic panels (PV) and solar thermal panels (ST). PV are able to sell electricity to the electric grid. In contrast, the CHP is not allowed to have any power transaction with the grid. A merit order is used as a control strategy for the system (Fig.2). Thus, to fulfill the heat demand technologies are used in the following order : CHP, ST, GB and then the EB. Furthermore, to satisfy the electricity demand, the CHP is used first and then PV panels. If these technologies are not sufficient to meet the load, electricity is imported from the grid. Finally, the electric boiler is powered first by PV panels and then by the grid. The values of constants and efficiencies are chosen based on [8].



**Figure 1.** Geographical location of the neighbourhood



**Figure 2.** Energy systems

## 3. Methodology

### 3.1. Energy systems modeling

- Electrical efficiency of the CHP  $\eta_{e,CHP}$  depends on the partial load ratio ( $PLR$ ) which is the ratio of the load to the nominal capacity :

$$\eta_{e,CHP} = a + b.PLR(t) + c.PLR^2(t) \quad (1)$$

where  $a = 0.1$ ,  $b = 0.4$  and  $c = 0.2$  are the electrical efficiency coefficients of the CHP [8]. The power production of the CHP  $P_{CHP}$  [ $\text{kW}_e$ ] and the recovered heat  $Q_{CHP}$  [ $\text{kW}_{th}$ ] are defined as:

$$P_{CHP}(t) = \eta_{e,CHP} Q_g(t) \quad (2)$$

$$Q_{CHP}(t) = \eta_{th} (1 - \eta_{e,CHP}) Q_g(t) \quad (3)$$

where  $\eta_{th} = 0.8$  is the thermal efficiency of the HRS and  $Q_g$  the CHP fuel gas consumption power [ $\text{kW}$ ].

- The gas boiler heat production  $Q_{GB}$  [ $\text{kW}_{th}$ ] is estimated from its conversion efficiency  $\eta_{GB} = 0.8$  by :

$$Q_{GB}(t) = \eta_{GB} \cdot Q_{g_{GB}}(t) \quad (4)$$

- The electric boiler heat production  $Q_{EB}$  [kW<sub>th</sub>] is given from its efficiency  $\eta_{EB} = 0.8$  by :

$$Q_{EB}(t) = \eta_{EB} \cdot P_e(t) \quad (5)$$

- The photovoltaic production  $P_{PV}$  [kW<sub>e</sub>] is calculated through a conventional model :

$$P_{PV}(t) = A_{PV} \eta_{DC/AC} \eta_{PV}(t) G_{\beta_0}(t) \quad (6)$$

with  $A_{PV}$  [m<sup>2</sup>] the solar PV panels area,  $\eta_{DC/AC}$  the inverters' efficiency,  $G_{\beta_0}$  [W m<sup>-2</sup>] the solar global radiation at tilt angle  $\beta_0 = 45^\circ$  and  $\eta_{PV}$  the photovoltaic conversion efficiency, expressed as a function of the cell temperature  $T_{cell}$  [°C]:

$$\eta_{PV}(t) = \eta_{ref} (1 - \alpha (T_{cell}(t) - T_{ref})) \quad (7)$$

With  $\alpha = 0.43\%/^\circ\text{C}$ ,  $T_{ref} = 25^\circ\text{C}$  a reference temperature and [8]

$$T_{cell}(t) = 30 + 0.0175 (G_{\beta_0}(t) - 300) + 1.14 (T_a - 25) \quad (8)$$

$T_a$  [°C] is the outdoor temperature [10]

- Solar thermal panels heat production  $Q_{ST}$  [kW<sub>th</sub>] is given by

$$Q_{ST}(t) = A_{ST} (G_{\beta_1}(t) \eta_0 - U_{loss} (T_{w,m} - T_a)) \quad (9)$$

Where  $A_{ST}$  [m<sup>2</sup>] is the total area of solar collectors,  $G_{\beta_1}$  [W m<sup>-2</sup>] the solar global radiation at tilt angle  $\beta_1 = 45^\circ$ .  $\eta_0=0.8$  is the optical efficiency of the collectors and  $U_{loss}=9.12\text{ W m}^{-2}\text{ K}^{-1}$  is their thermal loss coefficient and  $T_{w,m}$  [°C] the mean water temperature in the collector [8].

### 3.2. Load profile generation

For the campus buildings, measured electricity and heat consumption monthly data is available. Desegregation algorithms have been implemented to transform this data into hourly time series: the hourly heat demand is produced from monthly data using a degree-hour method [11]. Electricity consumption data is desegregated considering that the studied area is representative of the region's electrical uses'. Electricity consumption data of the region was scaled to obtain an hourly electricity load with a yearly consumption matching the yearly consumption of the campus. In contrast, data is not available for the 45 individual housings. Their total heat and electricity consumption (Fig.3) are obtained from simulations using SketchUp coupled to Trnsys to model typical residential houses complying with the french thermal regulation (RT2012).

### 3.3. Optimal design

The study purpose is to optimize the MES design for the studied zone. Decision variables are CHP, gas and electric boiler rated power [in kW], the surface available for ST [m<sup>2</sup>] and the fraction of thermal panels. A genetic algorithm is used to maximize two objective functions :

- **Annual total cost ratio (ATCR)** : the percentage of financial savings realized by the MES over a year, compared to a reference system (GB and power grid):

$$ATCR = 100. \left( 1 - \frac{ATC_{MES}}{ATC_{ref}} \right) \quad (10)$$

Where  $ATC_{MES}$  and  $ATC_{ref}$  are the annual total costs of the MES and the reference system respectively. They are obtained by adding operation and investment costs  $C_{O\&M,i}$  and  $C_{inv,i}$  modulated by the capital recovery factor  $crf$ . Fuel and electricity consumption

costs are estimated from  $C_g$  and  $C_{gr}$  their respective prices. The incomes from electricity selling at  $I_{gr}$  prices are considered :

$$ATC_{MES} = \sum_{i \in \text{subsys}} (C_{O\&M,i} + crf.C_{inv,i}) - \sum_{t \in [1,8760]} I_{gr}P_{sell}(t) + \sum_{t \in [1,8760]} (C_{gr}P_{gr}(t) + C_gQ_g(t)) \tag{11}$$

$$ATC_{ref} = C_{O\&M,GB} + crf.C_{inv,GB} + \sum_{t \in [1,8760]} (C_{gr}P_{gr}(t) + C_gQ_g(t)) \tag{12}$$

- **Annual operational cost ratio (AOCR)** : same as ATCR but without investment costs.
- **Renewable energy coverage rate (EnR)** : the percentage of energy consumed by the buildings locally and produced by renewable systems, solar collectors and PV panels :

$$\tau_{EnR} = 100. \frac{Q_{ST,consumed} + P_{PV,consumed}}{Q_d + P_d} \tag{13}$$

Investment and maintenance costs of the technologies as well as energy prices are given in table 3 and table 1. The considered ranges of optimization variables are given in table 2.

	0.12 (0h - 7h)
$C_{gr}$ [€/kWh]	0.13 (8h - 19h)
	0.15 (20h - 23h)
$C_g$ [€/kWh]	0.0615
$I_{gr}$ [€/kWh]	0.1

**Table 1.** Energies costs

Variable	Range
CHP rated power [kW]	100 - 1000
Gas Boiler rated power [kW]	100 - 3000
Electric Boiler rated power [kW]	100 - 3000
Solar surface [m <sup>2</sup> ]	0 - 10000
ST fraction [-]	0 - 1

**Table 2.** Ranges of the optimization variables

Tech	$C_{inv}$	$C_{O\&M}$
CHP	1140 €/kW <sub>e</sub>	21 €/MWh <sub>e</sub>
Gas Boiler	43 €/kW <sub>th</sub>	4.2 €/MWh <sub>th</sub>
Electric Boiler	32 €/kW <sub>th</sub>	3.7 €/MWh <sub>th</sub>
PV	4130 €/kW <sub>e</sub>	85 €/kW <sub>e</sub> /year
ST	615 €/m <sup>2</sup>	10 €/m <sup>2</sup> /year

**Table 3.** Maintenance and investment costs

#### 4. Results and discussion

Figure 4 shows two Pareto fronts : the first is obtained by optimizing ATCR and  $\tau_{EnR}$  and the second by optimizing AOCR and  $\tau_{EnR}$ . In the case of total cost optimization, the whole Pareto front is located in a region with negative cost savings which means that total costs of systems considering renewable energy sources integration is higher than the total cost of the reference case. Indeed, considering this study prices, the use of renewable energy systems rises the total cost compared to the boiler only system. Selling electricity to the grid does not compensate these high costs. Furthermore, the highest renewable energy coverage rate for this case is around 12 % with 9144 m<sup>2</sup> of PV and ST surface used. 32.2% of this surface is dedicated to ST. The rated powers of the CHP, the GB and the EB are respectively 118.2 kW<sub>e</sub>, 1928.4 kW<sub>th</sub> and 293.8 kW<sub>th</sub>.

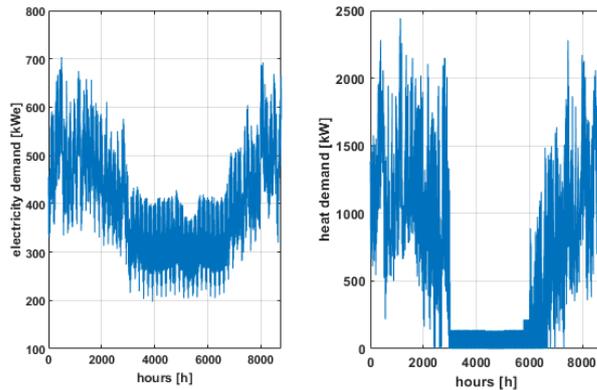


Figure 3. Heat and electricity loads of the buildings

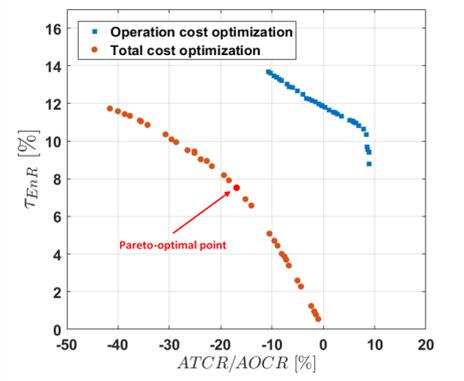


Figure 4. Optimal solutions

When only operation costs are considered in the optimization process, energy savings are negative when  $\tau_{EnR}$  higher than 12% and positive for lower renewable energy coverage rates. The Pareto front has a smaller width. It is due to the fact that renewable technologies have small operation costs compared to CHP and boilers. The highest renewable energy coverage of 13.7% in this case is obtained with a total PV and ST surface of 8062.3 m<sup>2</sup>. 31.6% of this surface is dedicated to ST. The rated powers of the CHP, the GB and the EB are respectively 129.5 kW<sub>e</sub>, 523.7 kW<sub>th</sub> and 1677.6 kW<sub>th</sub>. The higher renewable energy coverage compared to the first case is explained by the fact that a bigger electric boiler promotes local electricity consumption produced by PV. This part of PV production consumed locally is included in  $\tau_{EnR}$  calculation.

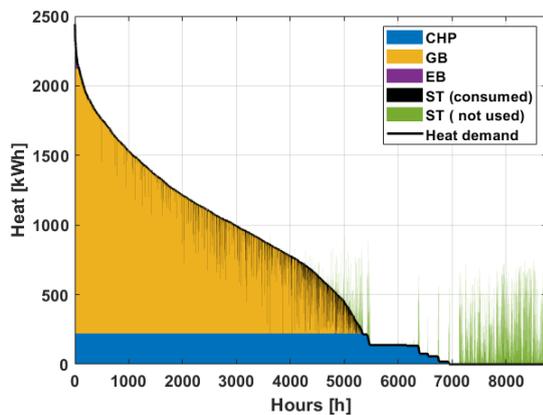


Figure 5. Heat duration curve

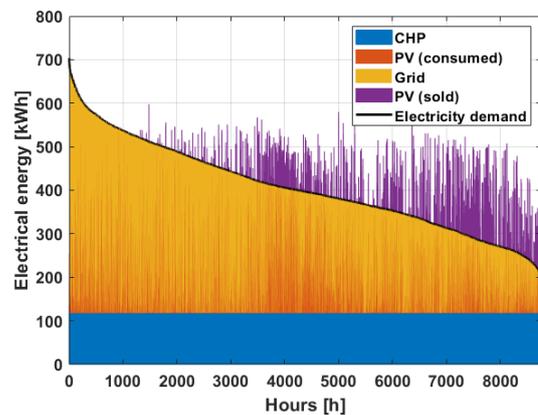


Figure 6. Electricity duration curve

Figure 5 and 6 present heat and electricity duration curves of the total cost optimization chosen solution. The studied optimum is an arbitrary choice but corresponds to a balance between the two objective functions. It has a  $\tau_{EnR}$  of 7.5% and ATCR of -17%. Duration curves for heat and electricity are given in figures 5 and 6. Heat consumption is over 0 kW only 7000 hours in the year (Fig.5). This is due to the domestic hot water profiles of the single-house in summer that are non-zeros for a few hours a day only. We notice a very small use of the EB (Fig.7) and relatively small use of ST to provide heat to the buildings (Fig. 5). Moreover, an important amount of heat produced by ST is not valued as it is not consumed (475 kWh over the

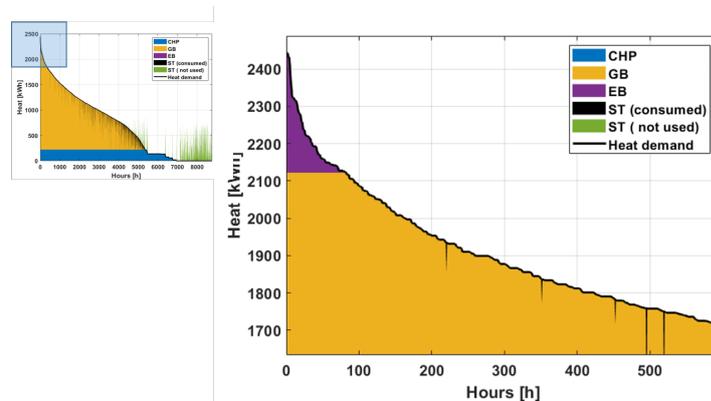


Figure 7. Heat duration curve (Zoom)

664 kWh produced). It is the case in summer, when the heat load is very low compared to ST production. A seasonal thermal storage for the excess of heat could be interesting. PV panels play a bigger role by providing electricity to the buildings and selling a part of its produced power to the grid (Fig.6). It is clear here that selling electricity is more profitable than using it to run an EB. This result depends on the point selected on the Pareto front.

## 5. Conclusion

In this paper, an optimization study was performed to design a MES providing heat and electricity to a neighbourhood in Nantes.

Considering operation and investment costs, the study shows that RES integration leads to higher total costs compared to a boiler only system. Indeed, a renewable energy coverage rate of 12% can be reached with more than 40% of extra cost compared to the reference case. Considering operation costs only, results are different and demonstrate that it is possible to reach a RES coverage rate of 12% while realizing cost savings. This RES coverage rate could be increased by implementing seasonal thermal storage to value ST production in summer.

These results are obtained using an energy management strategy assumed. For example, CHP can be controlled to meet heat demand instead of electricity demand. It can also be allowed to sell electricity to the grid or to provide electricity to the electric boiler. Further investigation are necessary to determine the optimal strategy to be used. A sensitivity analysis to understand which input parameters are the main drivers of the optimal solution is suggested to identify future changes and make more renewable neighbourhoods a feasible solution.

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