A heat piloted 5 kW fuel cell

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Introduction

Micro-cogeneration in residential applications is one of the efficient ways of improving the energy conversion efficiency in buildings. Cogeneration systems will cover electrical and thermal needs while reducing both energy bills and CO_2 emissions. Thanks to its high efficiencies, SOFC (Solid Oxide Fuel Cell) seems to be one of the major emerging technologies in this field.

The optimal design and operation of such a system will contribute to its profitability, a system analysis is therefore necessary. In a residential fuel cell installation project, the three following steps will be essential:

- Measurement or evaluation of thermal and electrical requirements profiles;
- Optimal system design and equipment rating;
- Optimal operation and control strategy of the heat/electricity management.

The measurement and the analysis of the electrical, Domestic Hot Water (DHW) and heating demands profiles as well as climate parameters for a single family house (Green Family Project[1]) in the region of Liege (Belgium) (annual thermal consumption: 25 MWh, annual electrical consumption: 20 MWh) has been performed.

A detailed study of the system's design (including a grid-connected and uninterruptible SOFC ($5kW_{el}$, $6\ kW_{th}$), the thermal storage, the thermal circuit and circulators) to meet these requirements has been performed. A linear programming formulation has been developed to model the optimal response of a given design in a given economical context.

Based on the demands defined with the measured data, the optimal operation of the system on a daily basis has been studied and the influence of the major design parameters such as the size of the storage equipment has been studied. A typical result is presented on figure 2, where we identify both the consumptions and the optimal production strategy for this system, taking into account the possibility of selling electricity to the grid. This approach is used to define a control strategy that will satisfy both heat and power demand and that will lead to performances as close to the optimal ones as possible. The goal of such a system is to minimise the overall emissions of the house under study. This goal may be in conflict with the goal of maximising the profit of the installation. Therefore a multi-objective optimisation strategy has been adopted. Two criteria have been used: operating cost reduction and CO_2 emissions reduction, assuming that the inhabitant's comfort objective is fulfilled by using the former consumptions. A single-objective optimisation technique based on linear programming problem has been used to analyse the sensitivity of the two objectives. Then a multi-objective optimisation technique based on the evolutionary algorithms developed at EPFL has been used to represent the trade-off between the 2 targets.

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[1] Green Family is the acronym for a research project funded by Walloon Region (Belgium) on the period 2001-2005, devoted to a demonstration of the ability to fulfil residential demand using a fuel cell system.

1. Defining the house requirements

The following data were continuously recorded at a frequency of 15 minutes on a typical residential house (single family, 5 persons) in Belgium near Liege (from January 2001 to December 2003):

- Space heating needs (Figure 1 and Figure 2)
- Domestic hot water needs
- Electrical consumption (Figure 4)
- Outdoor temperature
- Indoor temperature
- Boiler’s outlet temperature (= radiator’s inlet temperature) (Figure 3)
- Solar (Figure 5)
- Wind

Figure 1 shows the data for space heating for a warm day of winter 2002. We see the morning’s start demand. This important amount of energy is due to the increase of the set point in the rooms (from 18°C to 23°C).

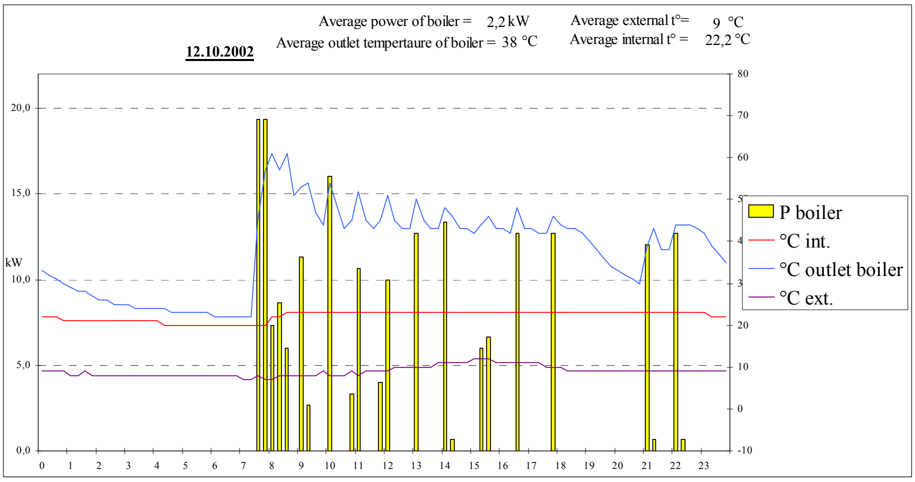

Figure 1: Measurements of space heating needs during 24 hours (Left scale: Thermal Power; right scale: temperature(°C))

Thermal needs (Space heating + Domestic Hot Water)

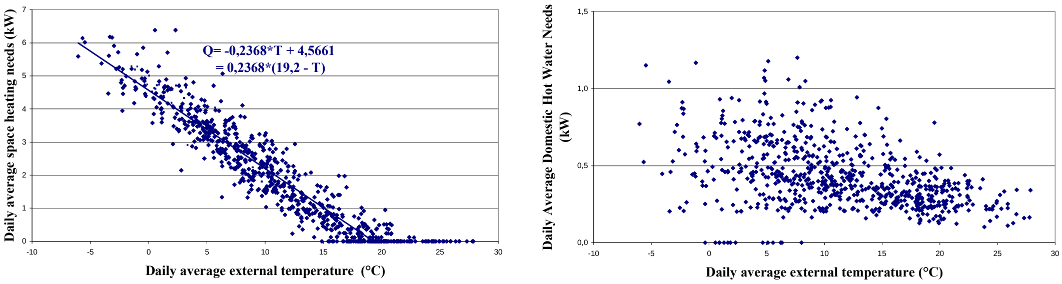

Figure 2 : Average daily space heating needs (kW) and domestic hot water needs (kW) vs daily average external temperature

Boiler’s outlet temperature

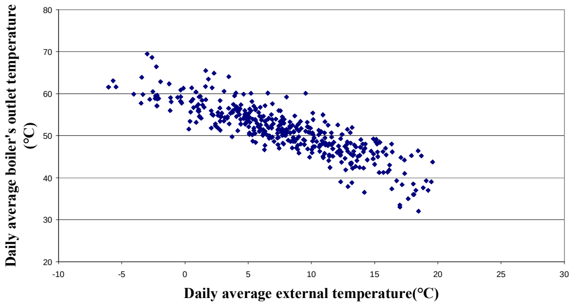

Figure 3: Daily average boiler's outlet temperature vs daily average external temperature

Electrical needs

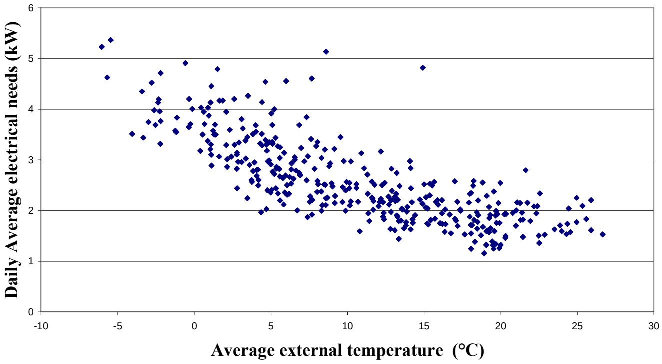

Figure 4: Daily average electrical needs vs daily average external temperature

Influence of solar radiation on space heating needs

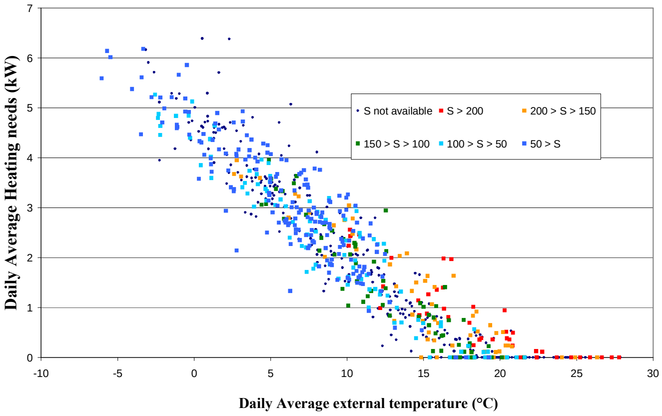

Figure 5 :Daily average space heating needs vs daily average external temperature (parameter radiation S (W/m²))

2. Description and model of the installation

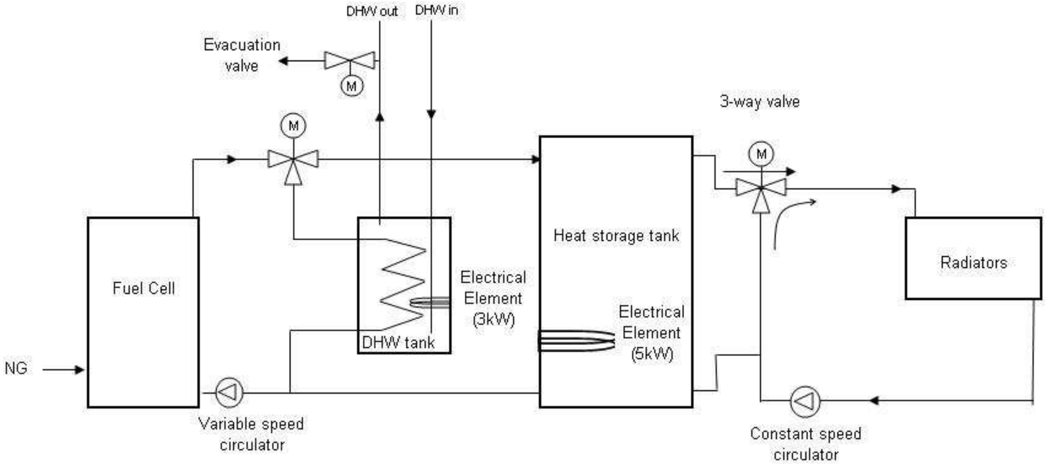

Figure 6: Diagram of the fuel cell system's installation

The installation (Figure 6) is composed of a fuel cell system fueled with natural gas (NG), a DHW tank (with internal heat exchanger, additional electric element (3 kW)), a heat rejection device, a heat storage tank (with additional electric element (5kW)), a 3 way valve for temperature regulation, radiators, a variable speed circulator, a constant speed circulator and pipes. The model of this system is based on thermal flows between the fuel cell (FC), the tanks and the heat distribution system.

Fuel cell

The heat production of the grid connected and uninterruptible fuel cell (SOFC) can be either brought to the DHW or to the heat storage tank. When DHW needs appears, the fuel cell can heat the DHW tank and the heat storage tank can continue to feed the distribution system. The variable speed circulator allows controlling the fuel the cell's outlet temperature. Assuming that we're working with a high temperature fuel cell (700°C), hot water production up to 80°C is possible. The electrical power (resp. thermal) of the fuel cell is supposed to vary continuously from 1,5 kW_{el} to 5 kW_{el} (resp 1,6 kW_{th} to 5,6 kW_{th}). Electrical (resp. thermal) efficiency is supposed to be constant and equal to 40% (resp. 45%) on NG LHV basis in the whole range (from 20% to 100% of the nominal power). These values represent the level of performance that is supposed to be reached by SOFC systems in the future. We assumed as a first assumption for the model development that the efficiency will not vary a lot with the level of utilization. If this points reveals to be critical, the model may be adapted either by using piece wize linearization techniques or by developing non linear models. The thermal efficiency is supposed to be independent of the inlet water temperature and flow.

DHW tank

The temperature of the DHW tank (called $t_{water\ stock}$) is supposed to be homogeneous (min 50°C, max 80°C) to supply DHW needs. These have been considered as being the measured data (called $Q_{water\ stock\ out}$). Thermal losses are neglected. A cheap heat rejection device is included in the installation in case of overheating of tanks caused by the uninterruptible fuel cell. Of course the use of this device must be avoided. In the system's dimensioning phase, we will impose the evacuation to be null.

Heat storage tank

The heat storage tank temperature (called $t_{heat\ stock}$) is also supposed to be homogeneous. In reality, the tank should preferably be stratified in order to maximise the thermal efficiency of the fuel cell. The maximum temperature (called t_{max}) is 80°C. This value influences quite a lot the optimal volume of the heat storage tank. The minimum storage tank temperature (called T_{req}) is varying with time. It depends on the heat to be supplied to the heat distribution system and therefore it would have to depend on climatic conditions, the way the house is used and the required comfort of the inhabitants. In our model, the temperature level required by the heating system simply comes from the measured data of boiler's outlet temperature (= radiator's inlet temperature). At each time of operation, the heat stock temperature must be higher than the required temperature to ensure the production of the heating service and guarantee the level of comfort. If we don't impose such a lower limit, the tank should contain enough energy to heat rooms but wouldn't be hot enough. The radiators shouldn't dissipate this energy. At the present time we have not developed a building model to compute the expected energy requirement. We assume therefore that the system has to behave exactly in the same way as it behaves in the present time with a conventional boiler. Further improvement should be made in the future to take advantage of future adaptation of the heat distribution control strategy, the passive heat storage in the house as well as the possibility of adapting the comfort requirements in order to maximise the profit of the system.

The 3 way valves will allow the regulation of the radiators' inlet temperature.

Thermal losses of the heat storage tank (called $losses_{heat\ stock}$) have been considered as a function of the storage size using the coefficient k_{losses} (corresponding to losses of 10% of the maximum energy stored per day) and thanks to the temperature difference between $t_{heat\ stock}$ and t_{room}. The model formulation of the storage tank remains by this way linear.

Other hypothesis

- The system is operated to supply the heating and the DHW requirements
- The tanks' energy level will be identical at the beginning and at the end of the day.
- Electricity, eventually optimally produced, is either consumed by the house's appliances or sent to the grid. No significant local electrical storage is included in the system.
- There is no additional boiler in the installation. Additional electric elements are playing the role of additional source of heat.

Equations

$$\frac{el[t]*eff_{th}}{eff_{el}} - Q_{water\ stock\ in}[t] - Q_{heat\ stock\ in}[t] = 0 \qquad [1]$$

$$K_{heat\ stock}[t] = K_{heat\ stock}[prev(t)] + (Q_{heat\ stock\ in}[t] - Q_{heat\ stock\ out}[t] + E_{heat\ stock}[t] - losses_{heat\ stock}[t])*duration[t] \qquad [2]$$

$$k_{losses\ heat\ stock} = percent_{losses}/100*vol_{heat\ stock}*\rho*c_p*(t_{\max} - t_{room})/3600 \qquad [3]$$

$$losses_{heat\ stock}[t] = \frac{k_{losses\ heat\ stock}}{24} * \frac{(t_{heat\ stock}[t] - t_{room})}{(t_{\max} - t_{room})} \qquad [4]$$

$$K_{heat\ stock} = (t_{heat\ stock}[t] - t_{room})*vol_{heat\ stock}*\rho*c_p/3600 \qquad [5]$$

$$\mathrm{K_{heat\ stock}} \le (\mathrm{t_{max}} - \mathrm{t_{room}})*\mathrm{vol_{heat\ stock}}*\mathrm{r}*\mathrm{c_p}/3600 \qquad [6]$$

$$K_{heat\ stock} \geq (t_{req}[t] - t_{room}) * vol_{heat\ stock} * \rho * c_p / 3600 \tag{7}$$

$$K_{water\ stock}[t] = K_{water\ stock}[prev(t)] + (Q_{water\ stock\ in}[t] - Q_{water\ stock\ out}[t] + E_{water\ stock}[t] - evac[t]) * duration[t] \tag{8}$$

$$K_{water\ stock} = (t_{water\ stock}[t] - t_{room}) * vol_{water\ stock} * \rho * c_p / 3600 \tag{9}$$

$$K_{water\ stock} \leq (t_{\max\ water} - 15) * vol_{water\ stock} * \rho * c_p / 3600 \tag{10}$$

$$K_{water\ stock} \geq (50 - 15) * vol_{water\ stock} * \rho * c_p / 3600 \tag{11}$$

$$el[t] + el_a[t] - el_v[t] - cons_{el}[t] - E_{heat\ stock}[t] - E_{water\ stock}[t] \tag{12}$$

3. Optimization

When considering the fuel cell system presented in the previous section, we wanted to answer the following questions:

"What's the optimal operation of the fuel cell system with fixed volumes for heat storage and DHW tanks on a daily basis?"

"What are the optimal volumes for the heat storage and DHW basis on a yearly basis?"

We have defined clearly the objective function to represent the optimal operation. Then, we have briefly presented the constraints, single-objective and multi-objective optimization technique used. Then, thanks to the single-objective optimization technique, we have evaluated the two optimal operation of the system on a daily basis (economical and ecological) and the optimal size of storage equipment. Finally, thanks to the multi-objective optimization technique, we have represented the trade-off between the two targets.

Constraints

- $E_{heat\ stock}[t] \in [0-5]$ [kW].
- $E_{water\ stock}[t] \in [0-3]$ [kW].
- Heat storage tank volume is limited to a minimum of 0,1 m^3 to avoid false optimums.
- The DHW tank volume is limited to a minimum of 0,01 m^3 to avoid false optimums.
- $t_{heat\ stock}[0h] = t_{heat\ stock}[24h]$.
- $t_{water\ stock}[0h] = t_{water\ stock}[24h]$.
- $t_{heat\ stock}[t] \in [T_{req} - 80]$ [°C].[2]
- $t_{water\ stock}[t] \in [50-80]$ [°C].
- $el\ [t] \in [1-5]$ [kW].

Objective functions

Objective functions are the functions that will be optimized. They must be chosen in order to express the desired behaviour of the installation. Three criteria were defined:

- J_1: The inhabitant's comfort
- J_2: The reduction of CO_2 emissions
- J_3: The reduction of operating cost

The definitions of the objective functions will be made on a daily basis. Note that we will define and optimize the "reduction" of CO_2 emissions and not the "CO_2 emissions" or the "percentage of reduction of CO_2 emissions". The three objective functions may be combined to form a single-objective function $J = \alpha J_1 + \beta J_2 + \gamma J_3$ and make a single-objective optimization.

J_1: Inhabitant's comfort

We introduce the following definition:

$$J_1 = \int_{day} \left\{ \underbrace{neg(T_{rooms,calulated} - T_{rooms,desired})}_{Space\ heating} + \underbrace{\delta.neg(T_{water,calculated} - T_{water,desired})}_{Hot\ water} \right\} dt \qquad [13]$$

In this function, only time periods with calculated temperature under desired ones are taken into account. As long as we didn't introduce a house's model but used measurement, this objective function will be directly fulfilled, that's why we won't have to optimize it in the scope of this work. The use of a linear programming strategy allows to formulate this objective as a constraint in this problem.

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[2] T_{req} is given by the measured data of boiler's outlet temperature

J_2: Reduction of CO_2 emissions

The reduction of CO_2 emissions J_2 (gCO_2) can be defined as the difference between:

- the amount of CO_2 (called $E_{CO_2,without\ FC}$) released by the former installation (boiler + grid) to deliver an amount of heat Q and an amount of electricity E and;

- the amount of CO_2 (called $E_{CO_2,with\ FC}$) released by the new installation (fuel cell system + grid) to deliver Q and E.

$$J_2 = E_{CO_2,without\ FC} - E_{CO_2,with\ FC} \tag{14}$$

$$E_{CO_2,without\ FC} = Q/\eta_{boiler}.g_{CO_2,GN} + E.g_{CO_2,elec} \tag{15}$$

$$E_{CO_2,with\ FC} = G.g_{CO_2,GN} + L.g_{CO_2,elec} \tag{16}$$

$$Q = \sum_t \left(\frac{el[t]}{eff_{el}}.eff_{el} + E_{heat}[t] + E_{water}[t] - losses_{heat\ stock}[t] - \kappa.evac[t] \right).duration[t] \tag{17}$$

$$E = \sum_t cons_{el}[t] * duration[t] \tag{18}$$

$$G = \sum_t el[t]/eff_{el} \tag{19}$$

$$L = \sum_t (el_a[t] - el_v[t]).duration[t] \tag{20}$$

Q is the amount of heat produced by the new installation during the period (day), it includes the thermal production of the fuel cell $\frac{el[t]}{eff_{el}} * eff_{th}$, the thermal production of the auxiliary electric equipment (in the heat stock and DHW stock) $E_{water} + E_{heat}$, the losses of the heat stock and evacuation.

E is the electrical consumptions of house's electrical appliances.

To deliver Q and E, the fuel cell and the new installation consume G [kWh] of natural gas. The excess in electricity generation (called el_v) is sent to the grid and the in-house additional electricity consumption (called el_a) is taken from the grid, "L" is the electricty balance of the system (A positive value of L means that electricity is extracted from the grid).

$g_{CO_2,GN}$ is the reference coefficient of CO_2 emissions for the natural gas: 249 gCO_2/kWh_{NG}. $g_{CO_2,elec}$ is the reference coefficient of CO_2 emissions for the electricity generation : 455 gCO_2/kWh_{el}. These are reference value for the calculation of CO_2 savings in the Walloon Region of Belgium. $g_{CO_2,GN}$ includes the production, transportation and combustion of NG. $g_{CO_2,elec}$ is based on electricity generation from a combined cycle facility (η=55% using NG LHV). η_{boiler} = 90%

When electricity is used to produce hot water (for DHW or heating), it is accounted as a thermal production

The factor κ is an additional coefficient to reinforce the negative weight of the evacuation of heat and favour solutions without evacuation. If this coefficient isn't inserted, the optimization tends to use more often the option to evacuate heat.

J_3: Reduction of operating cost

J3 is defined as:

$$J_2 = F_{without\ FC} - F_{with\ FC} \qquad [21]$$

$$F_{without\ FC} = Q/\eta_{boiler}.Tarif_{NG} + \sum_{day} cons_{el}.Tarif_{el\ b}.duration[t] \qquad [22]$$

$$F_{with\ FC} = G.Tarif_{NG} + \sum_{day}\left(el_a[t].Tarif_{el\ a} - el_v[t].Tarif_{el\ v}\right).duration[t] - el_{GC}.bonus_{GC} \qquad [23]$$

$$el_{CV} = sum\{t\ in\ TIME\}\ (el[t] - E_{heat\ stock}[t] - E_{water\ stock}[t])\ if\ > 0\ otherwise\ 0 \qquad [24]$$

The philosophy is the same as J_2. $Tarif_{el,a}$ and $Tarif_{el,v}$ depends on the hour of the day[3]. elGC is the electrical production of the fuel cell considered as "green production"[4]. It doesn't include the electrical production used for the additional electric elements.

Optimization methods

Two different approaches have been used to solve this optimisation problem. The single-objective approach has been used to compute on a time basis the performances of the system when it is operated in an optimal manner. The single objective optimisation solves day by day a linear programming problem. The method has been applied over the time period of the experiments in order to estimate the benefits that could be obtained by the new system by comparing the observed consumption with the bill of the new syste. Two objective functions have been considered successively: J2 : the CO2 reduction and J3 ; the cost reduction. The single objective approach has been used to compute the sensitivity of the design parameters on the performances. The second approach uses an evolutionary algorithm to solve a multi-objective optimisation that allows the calculation of the Pareto front

1) Single-objective optimization technique

The single objective optimisation problem has been coded using the AMPL[5] (combined with Minos or Cplex solver) :

Variables : $x=(x_1, x_2, x_3 \ldots x_n)=(el, el_a, el_v, E_{water}, E_{heat}, Q_{heat,stock} \ldots)$
Objective function : $f(x) = J$
Equality constraints : $C_e(x)=0$
Inequality constraints : $C_i(x)\leq 0$
Limits in variables $x_l<x<x_u$

The proper definition of maximum and minimum bounds is mandatory in this problem, in order to avoid trivial sub-optimal solutions.

2) Multi-objective optimization technique : QMOO[6]

QMOO is an evolutionary algorithm developed for solving multi-objective optimisations problems in the field of energy systems; it has been used to represent the trade-off between two criteria. It is an evolutionary algorithm. It works with an initial "population" of potential solution and converges via a genetic evolution mechanism to clusters of optimized solutions.

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[3] Hypothesis : el_a [23h-8h]=0,0758 €/kWh , el_a[8h-23h]=0,1573 €/kWh, el_v[23h-8h]=0,0238 €/kWh , el_v[8h-16h ; 20h-23h]=0,0376 €/kWh , el_v[16h-20h]=0,0700 €/kWh (April 2003)

[4] To promote "Green Cogeneration", the Walloon Government of Belgium has made eligible « green certifications » system. According to the level of performance of the CHP unit, a bonus is given for each kWh produced. For a SOFC system, $bonus_{GC} \approx$ 75 euros/3000 kWh

[5] Freeware available on www.ampl.com

[6] Developped at Ecole Polytechnique Federale de Lausanne (Switzerland) [QMOO]

Results

Numerical simulations were carried out over a time interval of one year (October 2002- November 2003), using the measured data set from the house described in Section 1. From this set, 6 "reference" days were taken (Figure 7). Four classifications have been done:

- cold days $T_{ext} < 0°C$;
- average days (1) (2) $0°C \leq T_{ext} < 5°C$;
- warm days (1) (2) $5°C \leq T_{ext} < 10°C$;
- hot days $10°C \leq T_{ext}$.

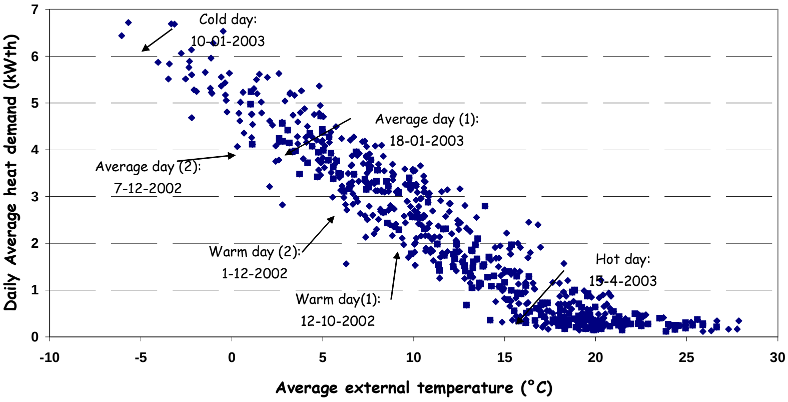

Figure 7: Reference days

For each "reference" day, the optimal operation of the system (for economical and ecological criteria) has been computed. Figure 8 shows the result of the optimal operation for the CO_2 reduction for the warm day (1) and Figure 9 shows the optimal operation for the cost reduction for the warm day (1)[7]. For this calculation, volumes of heat storage and DHW tanks have been fixed to 1,5 m³ and 0,2m³.

The graphs of the first line on Figure 8 and Figure 9 show the energy services requirements of the house under study. These values have been directly taken from the measurement data base[8].

The graphs of the second line show the optimal operation of the fuel cell, the distribution of heat to the storage and DHW tanks as well as the electrical element's production.

The graphs of the third and fourth line represent the balances:

- The optimal evolution of heat storage tank's temperature[9];
- The optimal evolution of DHW tank's temperature;
- The electricity exchange with the grid;
- The evacuation of heat, if necessary.

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[7] This day was represented on Figure 1 : Q= 2,2 kW ; T_{ext} =9°C

[8] Pay attention to the fact that space heating needs' scale is larger than others scales [0-20 kW].

[9] $T_{heat\ stock}$ (roze) must always be superior to T_{req} (red). Tres is given by the measured data : boiler's outlet temperature

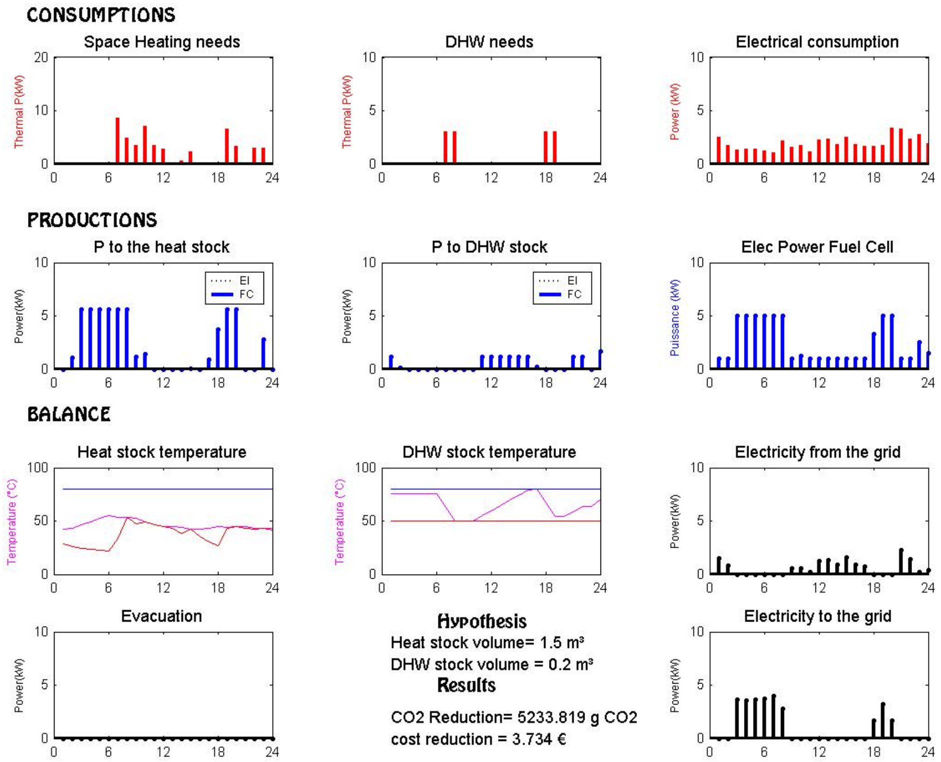

Figure 8: Optimal operation for warm day (1) - objective: CO2 reduction[10]

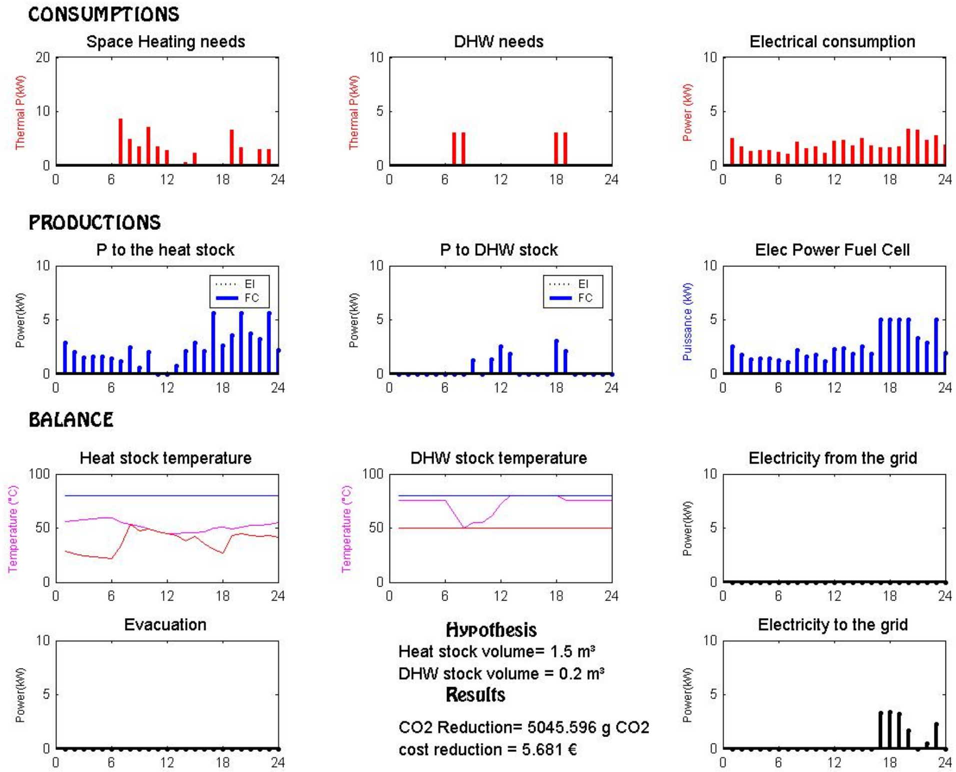

Figure 9: optimal operation for warm day (1) - objective: cost reduction

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[10] CO2 emissions (before) : 39 862 g CO_2 ; Cost (before) : 8,6 € - With classical system (boiler + grid)

Analysis

This example shows that the “cost” optimum is reached when the fuel cell power profile follows as much as possible the electrical consumption of the dwelling and when a minimum of electricity is taken from the electrical grid. The power of the fuel cell is limited during the night as much as possible to avoid selling electricity to the grid. During peak hours[11], the power of the fuel cell must be raised to the maximum level to take benefit of the “buy-back” prices. The “CO_2” optimum is reached when the fuel cell’s power is raised before the morning start demand.

The heat storage tank’s temperature follows a cycle between the maximum temperature at 6’o clock and the temperature reached at the end of the heating period. Heat stock temperature at 6’o clock and 23’o clock have been represented on Figure 10 for the “CO_2” optimal case. The lower the external temperature, the higher the heat stock temperature. In opposite with the former declaration, one signification exception occurs. During summer, heat demands are low, so that the temperature of the tank is always at its maximum.

The optimization has been performed with other “reference” days. Conclusions are the following:

- During the cold and the average days, the fuel cell is always working at his maximum power to cover heat demand. The power regulation of the fuel cell has little influence for these days. The two optimums (CO_2 and cost) are quite close for average days. The difference between optimums is more evident with hot and warm days.
- The days with bigger potentials of CO_2 and cost reduction are the average and cold days. Amount of energy undertaken are high for these days. Cold day has lower potential because the electrical elements are working more often. These conclusions are confirmed by Figure 11. Hot days (summer) lead to negative ecological performances. That is logical because the thermal demand is low (only DHW) and a heat rejection must occur because the heat storage tank’s temperature is high and the fuel cell can’t be stopped. In summer, the SOFC cell will have to be turned off (for CO_2 point of view, not necessary for cost point of view)

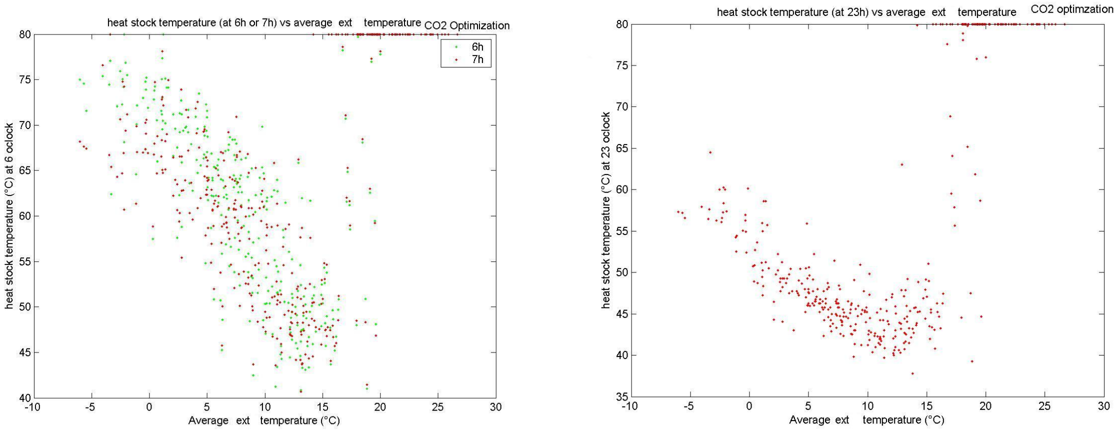

Figure 10 : Optimal heat stock temperature at 6’o clock and 23’o clock vs average external temperature (CO2 optimum)

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[11] Hypothesis : peak hours : 16h -20h

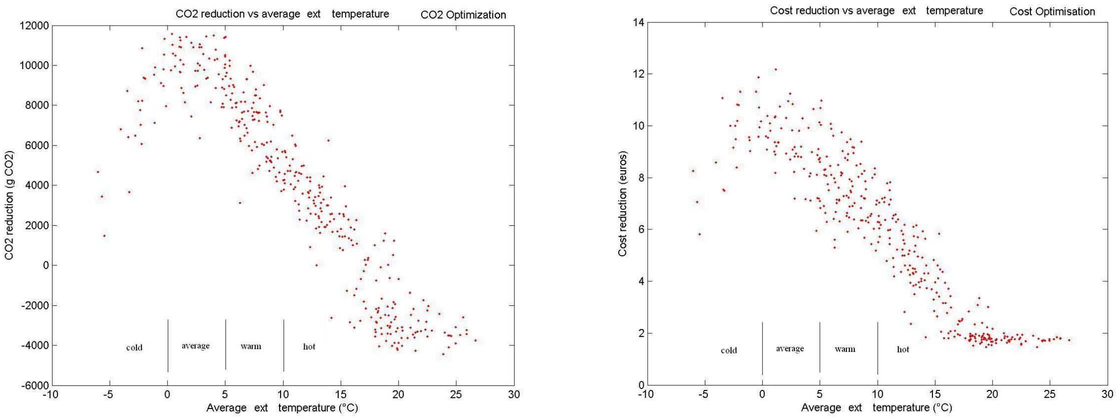

Figure 11: Cost reduction and CO2 reduction for optimal behaviour vs average external temperature (per day)

Optimal volume for the heat storage tank

Determining the optimal size for the heat storage tank is an important step in a residential fuel cell installation project. A small storage volume leads to a lower investment and minimizes the losses but don’t allow a easy running heat management. It’s easier to raise the fuel cell power during electrical peak hours (even if there are no thermal needs) and take benefit of it with a bigger tank. A big tank also minimizes the heat rejection.

Figure 12 represents the influence of the volume on CO_2 reduction or cost reduction volume over one year period. According to a criterion (cost or CO_2), a range of optimal volumes can be determined. This range is quite large. On these graphs, 1000 l. to 1500 l. are recommended for our application.

We have to remember that these curves are derived from an ideal optimized regulation. The simulation of performances and the determination of optimal volume should be done with real regulation to approach the real case.

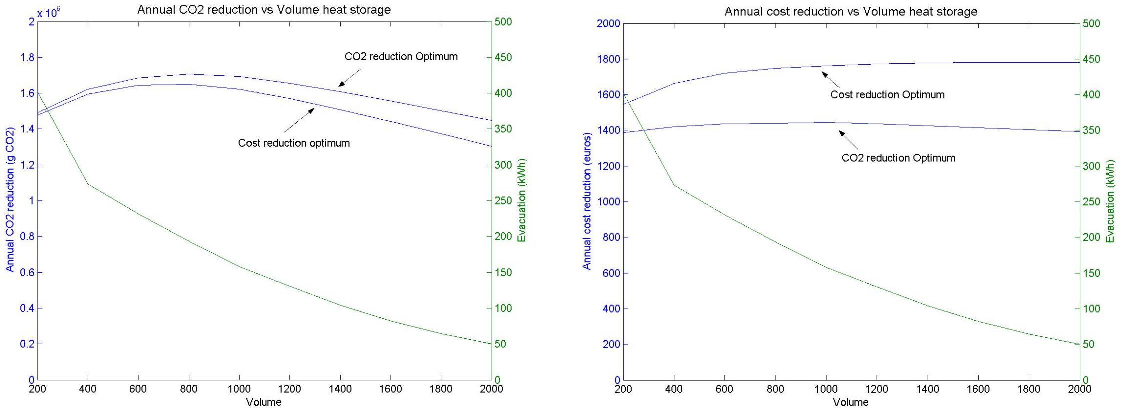

Figure 12 : Heat stock’s optimal volume

Knowing the optimal operation for economical or ecological criterion is very interesting. Off course, the users will try to operate there fuel cell to make a maximum of profit out of the investment. This will be possible if the optimisation procedure is embedded into the control system.

Another question is the analysis of the two optimisation criteria and the identification of the sensitivity of the cost parameters on both profit and emission reduction. A first question we tackled is to analyse the difference between the two criteria and the trade-off that may exists between the two criteria. The problem is solved by using multi-objective optimisation techniques

Figure 13 shows the initial random population used for the genetic algorithm process. Each point represents a particular operation of the system. Each of them delivers the right quantity of energy to the house. Ecological and economical optimums given by the single-objective optimization method have been added to the graph. For this warm day, ecological and economical optimums have approximately the same "CO2 reduction performance" but not economical performance. We see that a random control strategy of the residential fuel cell system would lead to performances far from the optimal ones..

Figure 14 shows the population reached by the algorithm after 10.000 evaluations.

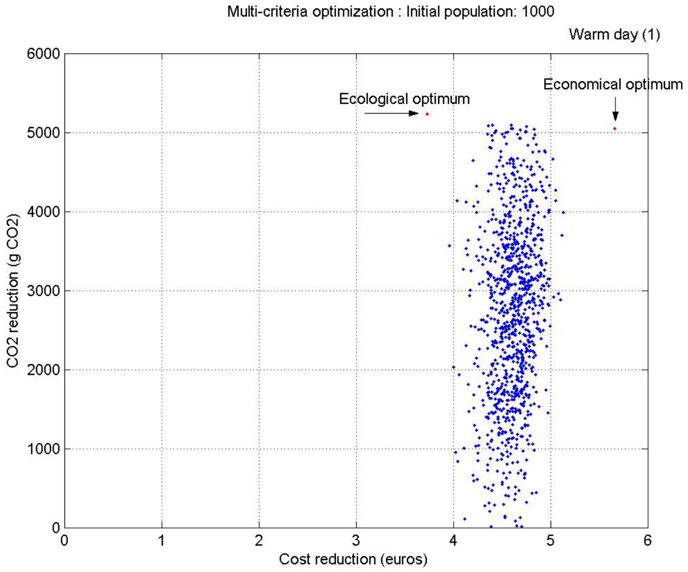

Figure 13: multi- objective optimization: initial population – warm day (1)

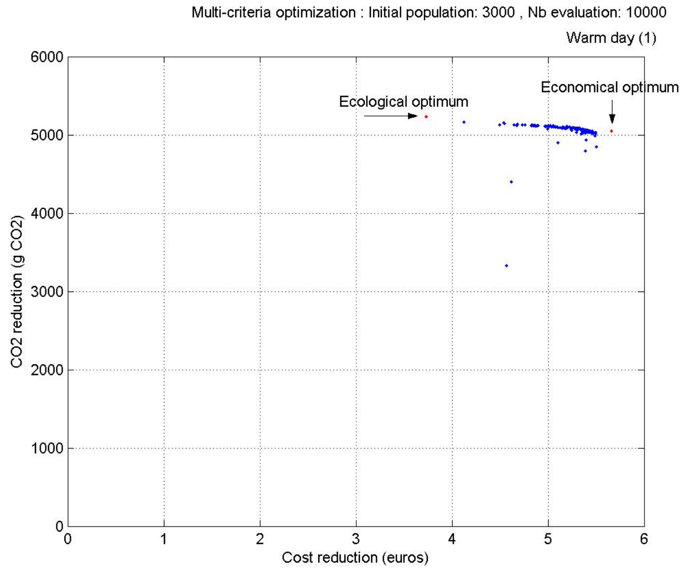

Figure 14: multi-objective optimization: after 10.000 evaluations– warm day (1)

Conclusion

A heat piloted SOFC fuel cell (FC) project for residential application is on its way in Belgium. Such application would need a complete review of the heat management of the house, needing a heat storage tank around 1.5 m^3 to follow the demand during a typical cold year in Belgium (the permanent 15 minutes average measurement performed during 2002 to 2004 help us to fix the worst mean daily power needed at around 6 kW of heat). The biggest interest to use fuel cell in the next future would be to limit green house gas (GHG) emission, even if the FC is fueled by natural gas (long term use will transfer input fuel to hydrogen produced by renewables which would put emission to zero level). But the market attack would need economical justification too. We developed an approach based on multi-objective optimisation (GHG and cost) which leads to substantial benefit compared to actual use of boiler + electrical network system at the same comfort level. The collaboration between two major actors in Europe (EPFL in Switzerland and ULg in Belgium) helps to profit of an optimal view on the best system to apply for FC residential application.

Symbols and Abreviations

$cons_{el}[t]$	Electrical consumption (lighting, oven,…) [kW]
c_p	Thermal capacity of water = 4,18 [kJ/kgK]
$el[t]$	FC electrical power [kW]
$\mathrm{el}_a[t]$	Electricity bought to the grid [kW]
$el_v[t]$	Electricity sold to the grid [kW]
eff_{th}	Thermal efficiency of the FC (45 %)
eff_{th}	Electrical efficiency of FC (40%)
$E_{heat\ stock}[t]$	Electrical power to heat storage by electric appliance [kW]
$E_{water\ stock}[t]$	Electrical power to water storage by electric appliance [kW]
$Evac[t]$	Evacuation [kWh]
$duration$	Time step [h]
$k_{losses\ heat\ stock}$	Thermal losses coefficient [kWh/jour]
$K_{heat\ stock}\ [t]$	Energy in heat stock a time t [kWh]
$K_{heat\ stock}\ [prev(t)]$	Energy in heat stock a time t-1 [kWh]
$K_{water\ stock}[t]$	Energy in water stock a time t [kWh]
$losses_{heat\ stock}\ [t]$	Losses of the heat stock [kW]
$percent_{losses}$	Percentage of losses compared to maximum 10 [%/jour]
$Q_{heat\ stock\ in}\ [t]$	Thermal power: FC to heat stock kW]
$Q_{heat\ stock\ out}\ [t]$	Thermal power: heat stock to house kW]
$Q_{watet\ stock\ in}\ [t]$	Thermal power: FC to water stock kW]
$Q_{water\ stock\ out}\ [t]$	Thermal power: water stock to DHW needs kW]
ρ	Specific mass of water = 1000 [kg/m³]
$t_{heat\ stock}\ [t]$	Heat stock temperature [°C]
$t_{water\ stock}\ [t]$	Water stock temperature d'ecs [°C]
t_{max}	Max temperature of heat stock [°C]
T_{ext}	Average external temperature [°C]
t_{room}	Reference temperature for room= 10 [°C]
$vol_{heat\ stock}$	Volume of heat stock [m³]

DHW	Domestic Hot Water
FC	Fuel Cell
HS	Heat Storage
NG	Natural Gas
LHV	Low Heating Value

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