Fuel Cell Economic Assessment for Residential Market

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Abstract: - The aim of this study is to investigate the economic viability of fuel cell (FC) applications in the residential market from the customer's viewpoint. An economic assessment of the technology is carried out by means of simulations of fuel cell's operation in a variety of residential segments. The segments considered are single family detached houses, duplex-triplex and multi-apartment buildings. For this purpose, a simulation code was developed by combining technical and economical variables with monitored energy data. Indicators such as payback period and breakeven cost have been determined under different scenarios. Additionally, a sensitivity analysis is conducted to determine the effect of technical and economical parameters on the FC economics. The investigated parameters include electric efficiency, FC capacity, battery storage and capital cost.

Key-Words: - Fuel cell, distributed generation, profitability, residential, economic assessment

1 Introduction

For the North American electric power industry, the need for system improvements is unavoidable. In conjunction with electricity deregulation and environmental needs pulling the market, and with years of research and development starting to pay off, the energy market in north America will probably experience an explosion of innovation in small-scale distributed generation technologies (DG) such as fuel cells (FC).

In this context, utilities should be concerned with the introduction of DG systems to the marketplace by studying the benefits of such systems and how they could be integrated into their resource strategy in the future. Depending on the market and their applications, DG can be seen from the utility viewpoint as an additional option to meet growth load and relieve transmission constraints while an end-use costumer will probably view DG as a way to reduce costs and obtain other benefits such as increased reliability and power quality.

This study provides a look at stationary FC profitability in Vermont state residential market from the customer's viewpoint. It identifies viable scenarios of FC operation and clarifies the influence of technical and economical parameters on the profitability[1] of FC systems.

2 Model overview

The tool developed for economic assessment of FC is based on the combination of energy data[2] with technical and economical parameters in order to calculate the annual payment and the present worth value under different scenarios of FC's operation.

A frequency approach is used under the following assumptions to perform energy analysis:

- A recurrent daily power demand profile is used to represent plug load requirements.
- Water heating consumption is represented by a mean demand independently of the day.
- Battery is allowed to achieve one cycle (charge/discharge) per day.
- Water heating has priority over space heating with respect to FC's heat rejection.

According to the first assumption, the daily electricity provided by the FC system (including battery) to the plug loads is given by the following equation:

$$E_{Plug}^{FC} = E_b + 24\,\Theta \sum_{i=0}^{P_{max}} \left[\left(f_{plug} \right)_i \cdot \min\left(P_{plug} \,;\, P_{nom} \right)_i \right] \tag{1}$$

where f_{plug} is the frequency distribution of the plug load demand obtained from measured data, Θ is FC annual availability (%) and E_b is the energy

1 All monetary calculations are based on US currency.

2 15 minutes intervals end-use power demand readings.

provided by the batteries while P_{plug} and P_{nom} represent plug load demand and FC nominal capacity respectively.

The amount of electricity purchased from the utility is calculated as follows:

$$E_{Plug}^{Utility} = \left(24 \sum_{i=0}^{P_{max}} \left(f_{plug}\ P_{plug}\right)_i\right) - E_{Plug}^{FC} \qquad (2)$$

As mentioned before, the heat generated by the FC is used first for water heating requirements and then the excess is provided for space heating. Furthermore the plug loads being fulfilled, the extra electricity generated by the FC can contribute to water heating and then to space heating if the source of energy for these two end-uses is electricity.

The part of generated energy available for water heating (DHW) represents the electric and thermal FC's generation minus the part of electricity required by plug loads, hence:

$$E_{Dhw}^{FC} = \mathrm{Min}\left[\underbrace{\left(\frac{E_{Plug}^{FC}\,\eta_{th}}{\eta_{el}} + \left(1+\frac{\eta_{th}}{\eta_{el}}\right)\times \alpha\left(24\cdot\Theta\cdot P_{nom} - E_{Plug}^{FC}\right)\right)}_{\text{available energy}} ;\ \underbrace{E_{Dhw}}_{\text{energy requirements}}\right] \qquad (3)$$

$$\alpha = \begin{cases} 1 & \text{for electric water heater} \\ 0 & \text{for gas fired water heater} \end{cases} \qquad (4)$$

η_{th}: FC recovery thermal efficiency
η_{el}: FC electric efficiency
E_{DHW}: energy requirements for water heating

The electric part of energy provided by the FC to water heating is given by the following equation:

$$E_{Dhw}^{FC_{el}} = \mathrm{Max}\left[\left(\frac{\left(E_{Dhw}^{FC_{tot}} - \frac{E_{Plug}^{FC}\,\eta_{th}}{\eta_{el}}\right)}{\left(1+\frac{\eta_{th}}{\eta_{el}}\right)}\right) ; 0\right] \qquad (5)$$

The part of generated energy (electric and thermal) made available for space heating (SH) is determined according to the following equation:

$$E_{Sh}^{FC_{tot}} = \left(24\cdot\Theta\cdot P_{nom} - E_{Plug}^{FC} - E_{Dhw}^{FC_{el}}\right)\left(1+\frac{\eta_{th}}{\eta_{el}}\delta\right)\cdot\beta + \delta\cdot \mathrm{Max}\left[\left(E_{Plug}^{FC}\cdot\frac{\eta_{th}}{\eta_{el}} - E_{Dhw}^{FC}\right) ; 0\right] \qquad (6)$$

where β and δ are control factors given by:

$$\beta = \begin{cases} 1 & \text{for electric SH} \\ 0 & \text{for gas SH} \end{cases} \qquad (7)$$

$$\delta = \begin{cases} 1 & \text{with co-generation for SH} \\ 0 & \text{without co-generation for SH} \end{cases} \qquad (8)$$

The economic assessment is based on a cash flow approach covering 15 years beginning from the date of investment. The net present worth is distributed equally over the entire period of analysis to obtain an annual payment. The annual payments (ANP) given by the following expression are used for economic calculation:

$$ANP = \left[\sum_{y=1}^{n} \frac{(C_{tot})_y}{(1+i)^y}\right]\cdot\left[\frac{i\cdot(1+i)^n}{(1+i)^n - 1}\right] \qquad (9)$$

where $(C_{TOT})_y$ is the sum of all costs: investment, energy bills, stack and battery replacements and finally maintenance cost at the y^{th} year while i is the market discount rate.

The FC economic viability to the customer is determined by comparing the ANP (i.e. FC operating costs) with the utility cost of delivered energy (electricity and eventually gas) represented by the reference annual payment ANP_{ref}. Money savings are generated if the difference between these respective quantities is negative. However, the project will go forward only if money savings are large enough relative to the investment required to meet the costumer's investment-return criteria

The payback period is used as an indicator for profitability evaluation. A more sophisticated expression (equation 10) that takes into account the effect of the market discount rate is used instead of the well-known ''simple payback''.

$$\mathrm{Payback} = \frac{\mathrm{Ln}\left(\frac{CRF}{CRF - i}\right)}{\mathrm{Ln}(1+i)} \qquad (10)$$

CRF is the capital recovery factor defined as:

$$CRF\ (\%) = \frac{\text{annual savings}}{\text{investment}} \qquad (11)$$

The energy bills are calculated according to the following electricity and gas rates:

Customer charge for electricity:	11.27	\$/month
Energy consumption:	0.11146	\$/kWh.

Customer charge for gas:	0.3363	\$/day
Energy consumption:	0.9607	\$/CCF[3]

3 Energy consumption data

Energy consumptions have been obtained from a database stemmed from a campaign of monitoring realized in Quebec over a period of more than a year.

Averaged energy profiles of space heating, water heating and plug loads have been extracted from the database for each segment considered say, detached family house[4], duplex-triplex[5] and multi-apartment[3] buildings (4-8 units). These profiles have been sorted in ascending order regarding to the power demand. The result of this manipulation is called the frequency profile representing the number (or percentage) of occurrence of power demand. The obtained profiles constitute the base of the approach adopted in this study (frequency approach). Data manipulation and the resulting frequency profiles for plug load and space heating requirements are presented below.

In addition to the segmentation of residential sector, each segment has been subdivided into three different sub-segments depending on the source of energy used to fulfill thermal requirements (space and water heating) such as:

Sub-segment	**Space heating**	**Water heating**
SH&HW_ELEC	electricity	electricity
SH_GAS	gas	electricity
SH&HW_GAS	gas	gas

Table 1 Segmentation versus source of energy

It should be noted that in reality, the energy profile coming from the original database are those corresponding to **SH&HW_ELEC** sub-segment in each residential segment. The energy profiles corresponding to the other sub-segments are obtained by switching the thermal requirements from electricity to gas and taking into account the thermal efficiencies of the corresponding gas equipment. For instance, the **SH_GAS** sub-segment is obtained by converting the water heating energy profile (initially electric) to gas considering the thermal efficiency of a gas fired water heater. The result represents the calorific contain of the consumed gas. Hence it is easy to calculate the quantity of the gas required for water heating. The same reasoning is applied for **SH&HW_GAS** sub-segment.

3.1 Plug load requirements

The power demand profile of plug loads has been sorted for each segment. The resulting frequency profile represents the number of occurrence versus power demand as depicted in figure 1.

It is shown that, in approximately 65 % of the time over a year, plug load power demand is below 1 kW for a single-family house while the frequency is approximately 55%, 35% respectively for duplex-triplex and multi-apartment buildings.

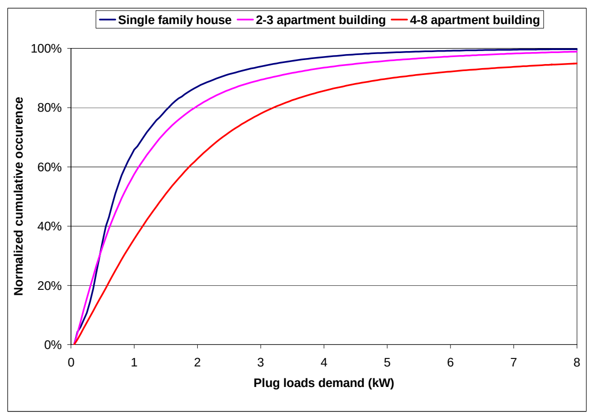

Fig. 1 Plug load frequency profile.

3.2 Space heating requirements

An energy analysis has been performed on the raw energy data (space heating readings) for a specific year to predict space heating requirements that are independent from climate variation. Indeed, the PRISM method has been used to determine the characteristics of the segment. These characteristics are represented by two factors: the mean heat loss coefficient of the shell (UA) and the equilibrium temperature at which the heat loss equals the internal gain (T_{eq}). Consequently, when the outdoor temperature is greater than the T_{eq} no heating is required. The results are summarized in table 2 for the different segments.

The heating load is predicted by the following equation:

[3] 1 CCF ≡ 1 Therms = 100 000 BTU

[4] Energy profiles of 57 single family detached houses are available for 1004 days at 15 minutes interval.

[5] Energy profiles of 51 duplex triplex and 52 multi-apartment buildings are available for 700 days at 10 minutes interval.

$$
Q_h = \begin{cases} UA(T_{eq} - T_{out}) & \text{if} \quad T_{out} < T_{eq} \\ 0 & \text{if} \quad T_{out} \geq T_{eq} \end{cases} \tag{12}
$$

Outdoor temperatures recorded at St-Hubert station (suburb of Montreal city) for a typical year have been used. The use of a typical year allows obtaining results that are independent from weather variations.

	Heat loss coefficient UA (kW/°C)	Equilibrium temperature T_{eq} (°C)
Single family	0.13	16.2
Duplex-Triplex	0.256	16.9
Multi-apartment	0.4044	16.3

Table 2 Characteristics of the building shell.

In order to take into account the number of apartments in segment 2 and 3, weight coefficients have been used to calculate a representative averages values for duplex-triplex and multi-apartment buildings. Then, the methodology described in the previous section has been applied to construct the frequency profile for space heating. In fact, similarly to the plug load demand intervals created from the corresponding power demand profile, the temperature bins are calculated using 0.6°C increments. The number of occurrence for each interval is calculated in term of percentage. The space heating load occurrences are obtained from their associated temperature occurrences for each interval by means of equation 1.

Figure 2 illustrates the normalized cumulated percentage versus space heating demand.

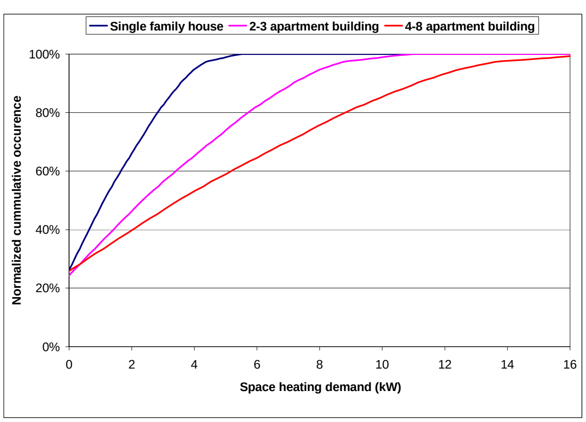

Fig. 2 Space heating frequency profile.

3.3 Water heating requirements

The water heating requirements are based on average daily energy consumption. Data readings [1], [2] reveal that the daily water heating consumption ranges approximately between 9 and 12 kWh/apartment. Figure 3 represents the annual power demand profile for water heating in a single family house. With an average power demand of 0.4665 kW, the daily energy consumption for water heating purpose is 11.2 kWh per day. Basically, the daily energy consumption for hot water in the different segments has been determined using the data collected over a longer period as mentioned above.

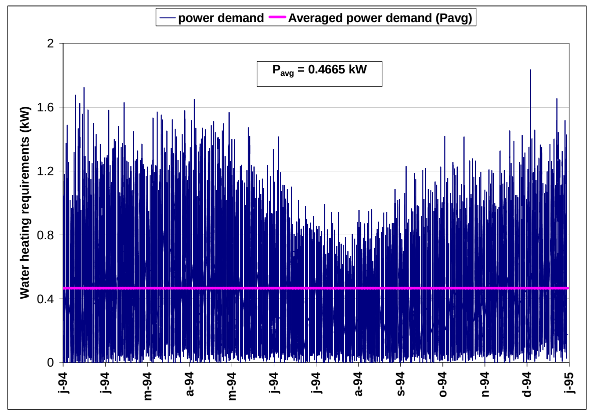

Fig. 3 Water heating power demands in single-family.

The results for the three segments are summarized in table 3. As mentioned above these results are valid for **SH&WH_ELEC** and **SH_GAS** sub-segments since the water heating is electric for these segments. The daily energy consumption and energy demand required for water heating should be increased for **SH&WH_GAS** sub-segment by introducing the thermal efficiency of the gas fired water heater.

	Single family	Duplex-Triplex	Multi apartment
average number of residential unit	1	2.41	5.78
daily energy consumption (kWh/unit)	11.5	9.7	8.9
mean demand (kW/unit)	0.48	0.40	0.37
mean demand (kW)	0.48	0.97	2.14

Table 3 Water heating requirements

4 Scenarios and parameters

Many operation scenarios of the FC have been examined in order to cover a variety of possible applications of the technology.

Six different FC system configurations are investigated in the present study. These configurations represent systems based on the use of co-generation and battery pack. It should be noted here that two situations are considered for co-generation: the recovered heat can be used to displace water heating requirements alone or both water and space heating requirements.

These FC configuration systems have been used for each residential sub-segment. The combination of the segments considered in this study and their corresponding sub-segments with the different configurations of the FC system yield to a total of 54 different scenarios that have been investigated.

The technical and economic parameters that are used as inputs in the model are as follows:

- FC capacity (kW)
- Battery electric output (kW)
- Battery storage capacity (kWh)
- FC electric efficiency (%)
- Recovery thermal efficiency (%)
- FC availability (hrs/year)
- System lifetime (years)
- Stack lifetime (hours)
- FC purchase and installation cost ($/kW)
- Maintenance cost per generated kWh ($/kWh)
- Replacement cost (% of FC purchase cost)
- Market discount rate (%)

The different values have been cross combined by varying one parameter into three different values (low, mean and high) and keeping the others fixed to study the impact of each of them on the money savings. Nevertheless, few parameters such as electricity and gas rates remain constant for all simulations. The cross combination of 12 parameters with three possible values yields to a number of 531441 cases to study for each scenario of operation.

The technical parameters have been obtained essentially from the manufacturers' publications and reports while the economic parameters are those popular in the marketplace.

Presently, the electric efficiency of the FC system (stack and reformer) is approximately 35% while the overall efficiency is approximately 65% in the case of co-generation. It has been deduced from these values that the thermal efficiency accounts for 30% from the overall efficiency. Concerning the FC availability, its minimal value has been estimated on basis of two weeks for annual maintenance (8400 hrs/yr) while the mean value corresponds to a shut down during one week. Finally, the maximal value represents the no stop situation: the FC runs for 8760 hrs/yr.

On the other hand, the current estimated cost of the technology is around $4500 per kW based on the price of PAFC manufactured by ONSI. It is probably higher for PEMFC and SOFC since these technologies are in the pre-commercial stage. The projected purchase cost for 2010 is estimated to $1500 per kW including the installation [3]. Furthermore, the battery purchase cost has been fixed to $150 per kWh.

Parameters	Low value	Mean value	High value
Electric efficiency (% LHV)	35	40	45
Recovery thermal efficiency (%)	30	35	40
FC availability (hrs/year)	8400	8600	8760
System cost + installation ($/kW)	1000	1500	3000
Maintenance cost ($/kWh)	0.006	0.008	0.012
System lifetime(yrs)	10	15	20
Stack lifetime (hrs)	35000	40000	45000
Replacement cost (%)	30	40	50
Discount rate (%)	8	10	12
Battery lifetime (years)	4		
Battery cost ($/kWh)	150		

Table 4 Parameters' variability

The installed capacity is one of the parameter that depends on the site characteristics. In fact, this parameter has been varied in accordance with the segment and the sub-segment as shown in table 6.

The maximum FC's capacity depends on the sub-segment. In fact, for all electric sub-segment (**SH&WH_ELEC**), the maximum capacity of the FC's system is chosen to meet the maximum power demand (total demand) over the year. It is obvious in the residential sector that the maximum power demand occurs during the coldest day. It should be noted that the space heating requirements (counting for at least 30% of the total requirements in the residential sector) are greater during this day.

For illustration, let's calculate the maximum total demand for a single family house. The temperature during the coldest day is around −25°C (design temperature), given the global loss coefficient and the equilibrium temperature (from table 1, UA = 0.130 kW/°C, T_{eq} = 16.2°C) and using equation 1, the space heating demand is estimated to 5.4 kW. In order to estimate an average total demand during the coldest day, the following average plug load and hot water requirements are taken: their respective values are 1.02 kW and 0.48 kW (see table 3 and 5). The addition of the different requirements yields approximately a total average demand of 7 kW. In this case, a 4 kW FC with co-generation is chosen. It is believed that for 97% of the time, the combination of the electric and thermal output of the FC will meet the total energy requirements of the building. Nevertheless, a battery is required to supply power when the plug load is greater than 4 kW.

Concerning **SH_GAS** and **SH&WH_GAS** sub-segments, the maximum capacity of the FC system is so that 97 % of plug load requirements are fulfilled. For example, a FC capacity of 3 kW is large enough to meet plug load requirements in a single family house according to table 5.

	Single family	Duplex-Triplex	Multi-apartment.
Average number of unit	1	2.41	5.78
Mean plug load (kW/unit)	1.02	0.57	0.43
Mean plug load (kW)	1.02	1.37	2.48
Plug load demand in 97 % of the time[6]	≤3 kW	≤6 kW	≤11.6 kW
Plug load demand in 99.9 % of the time[4]	≤10 kW	≤13 kW	≤28 kW

Table 5 Plug load requirements in the different segments

The minimum FC capacity has been fixed to the lowest FC capacity that some manufacturers are developing for the market under consideration. According to the manufacturers' announcements, there is no interest for FCs below 1 kW capacity in the residential stationary application. Hence, the FC capacity low value is fixed to 1 kW/residential unit.

In many scenarios, the FC is coupled with a battery where the later component is used as back up source of power. The battery is supposed to have enough energy to supply power continuously at the same rate for at least one hour during the peak period. Its minimum and maximum electric outputs are set to meet the plug load requirements in 97% and 99.9% of the time respectively. As an example, the FC of 4 kW chosen previously for an all electric single family house (**SH&WH_ELEC**) cannot satisfy the demand of 10 kW as given in table 5. In this case, a battery with a maximum electric output of 6 kW is added to the system. A larger battery with 7 kW electric output is coupled to the FC of 3 kW in the case of **SH_GAS** or **SH&WH_GAS** sub-segments.

Similarly, the minimum battery output is estimated such as its electric output meets 97 % of plug load demand. For instance, table 5 shows that in 97 % of the time the plug load demand is below 3 kW in a single family house. In this case, a system with a FC of 1 kW capacity coupled with a battery capable to supply an electric output of 2 kW will fulfill the plug load requirements in 97 % of the time. A minimal storage capacity of 2 kWh is used to provide an electric output of 2 kW during one hour. This reasoning is applied for all segments and their corresponding sub-segments to estimate the minimal battery output.

5 Results and discussion

A duplex-triplex building with an electric space and water heating system **SH&HW_ELEC**) has been chosen as an example to present the results of the economic assessment and the sensitivity analysis.

The results concerning the scenario mentioned above are displayed in figure 4. The figure represents the distribution of ANPs. It should be noted that the red line defines the ANP without a FC used as a reference for comparison purpose (ANP_{ref}). The blue curve represents the percentage of occurrence of all estimated ANPs. As mentioned before, a total of 531441 different ANPs are calculated. These ANPs are sorted into intervals incremented by $10 [$4005, $4015, …, $9985, $9995]. Then, the percentage of occurrence for each interval is calculated. For example, 0.12% of all the calculated values have an ANP in the interval of $7000±5. Finally, the green curve shows the cumulated percentage of occurrence corresponding to the sum (in percentage) of the cases with an ANP below the corresponding value on the ordinate axis.

For example, for an ANP of $7000 the cumulated percentage is approximately 85%. In other words, 85% of the 531 441 cases correspond to an ANP below $7000, say 451725 cases. It should be pointed that the later curve provides interesting information on the profitability. Indeed, the coordinate of the

[6] According to figure 1

intersection point of this curve with the vertical straight line represents the percentage of the cases where money savings can be generated. In the case of no intersection, the scenario does not generate any money savings. Figure 4 reveals that in 24% of the cases the ANPs are reduced compared to the corresponding reference ANP estimated to $5305.
The sensibility bar graph (figure 5) illustrates the effect of each parameter on the ANP obtained by fixing all the parameter to their mean values except for the parameter that the influence is under investigation. This effect is obtained by varying the variable parameter by ± 25% from its mean value except for FC's availability and market discount rate where the respective deviations are ±1.5% and ±20%. This procedure is repeated for each parameter separately.

This graph permits to evaluate the impact of all the parameters on the mean ANP and to identify the most influent ones. On the other hand, it represents an interesting source of information for the range of absolute changes of the mean ANP under variable parameters.

For instance, it has been observed that a change of –25% of purchase cost is followed by a decrease of $275 on the mean ANP. Symmetrically, the opposite trend is obtained for a positive deviation of +25%. Notice that the mean ANP is obtained by fixing all the parameters at their mean value.

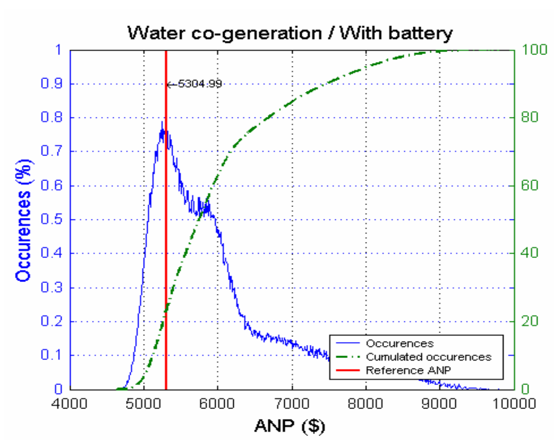

Fig. 4 Distribution of annual payments

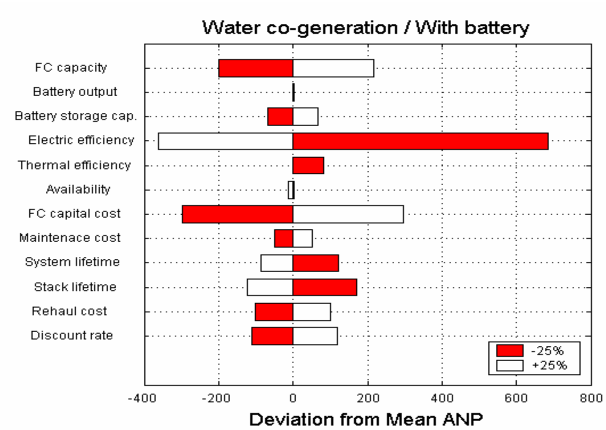

Fig. 5 Parameter impact on the annual payments

5.1 Payback period

The payback period has been calculated for all cases under the different scenarios defined previously. The results concerning **SH&WH_GAS** sub-segment are not presented because they generate no money savings or not enough to be interesting. The scenarios including batteries are also ignored in the presentation. The use of a battery does not offer an advantage compared to the scenario without battery: the percentage of profitable cases decreases when a battery is introduced [4, 5]. Thus the total of 54 scenarios collapses to 18 scenarios only.
Figure 6 displays respectively the payback distribution of the studied cases. It is observed that scenario 17 is the most interesting one since 79.5% of the cases generate money savings and 9.4% of the total cases present a payback less than 3 years. Situations with a payback that ranges form 3 to 5 years represent 18.6% of the total cases. The percentage increases for longer payback periods. In general, the highest percentages are found for a payback greater than 10 years. Paybacks less than 3 years are met under scenarios 11 and 17.

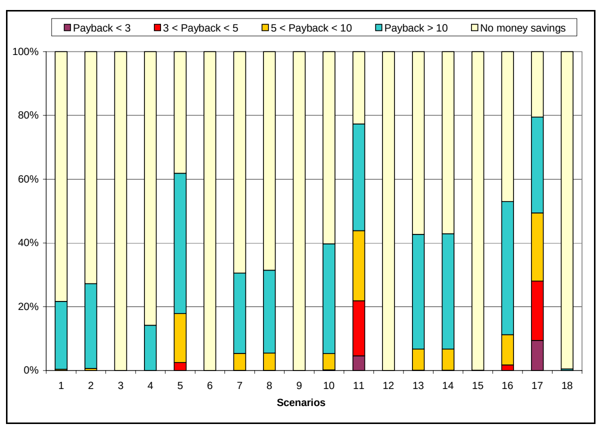

Fig. 6 Profitable cases by scenarios

5.2 Sensitivity analysis

The goal of the sensitivity analysis is to evaluate the effect of economic and technical parameter variability. Each of the parameters is changed by a certain fixed percentage, and the simulation is run with this new input. The absolute change in the annual savings is used as the gauge for sensitivity. The obtained results are presented in this section. As mentioned before, three different values are affected to each parameter (a total of 12 parameters) while the others remain fixed at their respective mean value.

As observed in figure 5 the purchase cost is the most influent economic parameter. If the mean purchase cost is reduced by 25% (from \$1500 to \$1125), the mean ANP decreases by a maximum of 9%. Symmetrically, a 25% increase of this parameter yields to an increase of the mean ANP by the same maximum percentage. The other economic parameters (such as maintenance cost, system lifetime, stack lifetime, replacement cost and market discount rate) have much less influence on mean ANP than the precedent one. It can be observed on the bar graph that these effects are approximately twice less important.

Regarding the technical parameters, the electric and thermal efficiencies are the most influent ones for **SH&WH_ELEC** sub-segment. A 25% reduction of the electric efficiency has a negative incidence on the mean ANP by a maximum decrease of 14%. The same reduction on the thermal efficiency has less impact on the mean ANP. Nevertheless, the FC capacity is the most influent parameter on the mean ANP in the case of **SH&WH_GAS** and **SH_GAS** sub-segments. In fact, results show that a 25% augmentation of this parameter increases the mean ANP by up to 8%. An opposite effect is observed when the value is decreased by the same percentage.

In order to show the impact of FC capacity and purchase cost on the percentage of positive cases, figures showing the percentage of positive cases for each cross combination of low, mean and high value of both parameters under investigation are presented. All cases are generated by fixing the respective values of these two parameters and by varying the value of the remaining ones. Figure 7 has one particularity: the FC capacity has two different values for the same point. This value depends on the source of energy used for heating. The ordinate 2-2.5 kW means that the FC capacity is 2 kW for **SH&HW_GAS** and **SH_GAS** sub-segments while 2.5 kW is relative to **SH&HW_ELEC** sub-segment.

As an example, for an all electric single family house, figure 9 shows that 15.5 % of all cases generate money saving if the purchase cost is fixed to \$3000/kW and the FC is 1 kW capacity. The percentage of positive cases corresponds to system's configurations that generate the most significant money savings. Previous results have permit to identify water/space co-generation without battery as being the most profitable configuration. No percentage is displayed on these graph for **SH&WH_GAS** sub-segment because all cases generate no money saving.

Figures 7, 8 and 9 reveal that the purchase cost is a determinant parameter. At \$1000/kW, a very high percentage (approaching 100%) of positive cases is obtained for **SH&WH_ELEC** sub-segment, regardless the building type and the FC capacity. This percentage is still high when the purchase cost reaches \$1500/kW, except where a large FC is used in the single-family segment. In this case, the percentage decreases drastically to 42.5%. The impact of this parameter becomes clear for \$3000/kW. Indeed, the percentage of positive cases in the single family segment drops to 15.5% with small FC and vanishes for larger ones. The same trend is observed for the other segments.

Similarly, the percentage decreases for **SH_GAS** sub-segment with increasing FC capacity for all purchase costs. The decrease is more pronounced for this type of heating system compared to the electric one. Moreover, the percentage is negligible even null for a purchase cost of \$3000/kW.

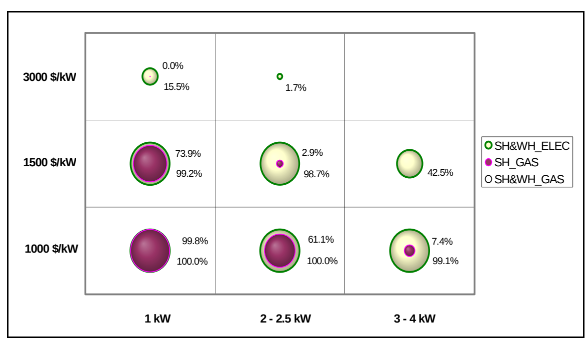

Fig. 7 Ratio of profitable cases in single-family

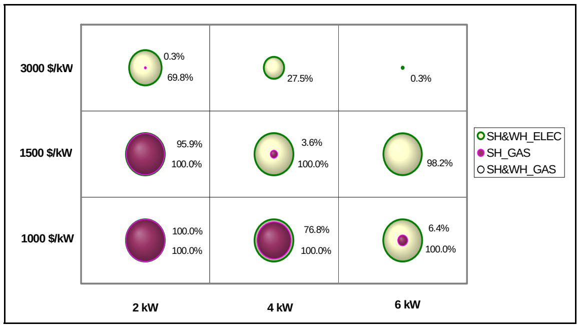

Fig. 8 Ratio of profitable cases in duplex-triplex

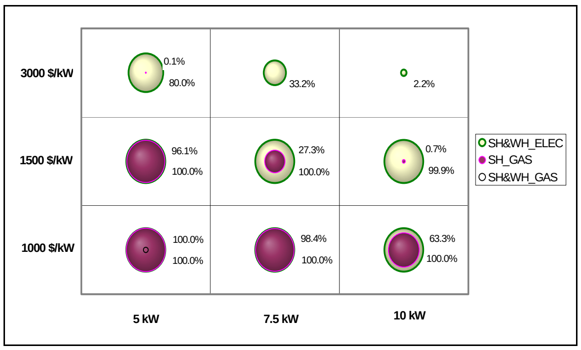

Fig. 9 Ratio of profitable cases in multi-apartment

6 Conclusions

The economic assessment revealed that the FC system might be interesting for residential segments where electricity is the only source of energy (**SH&HW_ELEC**). In multi-apartment building, the relative money savings could reach up to 21% annually with mean parameters. This limit is less for duplex-triplex building and single family house: 19% and 11% respectively. In contrast, no money savings are obtained when gas is used for water heating or for both space and water heating (**SH_GAS** and **SH&WH_GAS**) based on mean parameters. However, there exist cases that generate money savings with more optimistic parameters for **SH_GAS** sub-segment.

Concerning payback, results show that it could be less than 3 years under certain conditions but most of the cases present a payback ranging from 5 to 10 years and over. The shortest payback periods have been obtained in the case of **SH&HW_ELEC**.

On the other hand, large energy consumers seem to be the most attractive application for FC. Since the FC capacity has been chosen on the basis of electric requirements, the heat rejected must be recovered for heating purpose to maximize the system overall efficiency. Results have shown that the system investigated in the case of multi-apartment and duplex-triplex buildings are used more efficiently than those are in single family houses. This is probably due to the importance of thermal requirements that allow the use of the heat generated by the system.

It has been found in all cases that, the technology is not profitable when the heat generated by the fuel cell is not recovered (no co-generation). The payback calculation has shown that the most profitable configuration includes co-generation for both space and water heating. Furthermore, the use of battery is not profitable since the additional cost introduced does not generate significant extra money savings.

The sensitivity analysis shows that the FC capacity has a great impact on the profitability. Small systems are favored for their high seasonal efficiency and the relatively low investment requirement. Also, the monetary performance is affected negatively by poor overall efficiency of the FC system.

Finally, the purchase cost of the fuel cell system is identified as being the most influent parameter. In the short term, the technology does not seem to be economically attractive. At $3000/kW, the money savings are insignificant. Nevertheless, the long term system cost ($1000/kW) will likely allow the technology to be an interesting option for power generation. In this context, systems must be offered at a competitive cost to allow a potential market penetration.

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