Fuel Cells as CHP Systems in Commercial Buildings: a Case Study for the Food Retail Sector

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ABSTRACT

This study investigates fuel cells as combined heat and power systems (CHPs) for distributed applications in commercial buildings, specifically supermarkets. Up-to-date technical data from a specialized manufacturing company was investigated and used to conduct a case study analysis on several food retail buildings using half-hourly historical data. A detail mathematical model, described in previous publications (Cedillos et al. 2016, Acha et al. 2018), was used to simulate the performance of fuel cells through a year of operation in each supermarket. The simulations employ comprehensive energy market costing data and practical information to evaluate project feasibility such as installation work costs. The results of the simulations are discussed and a techno-economic assessment is conducted to evaluate the main factors affecting the economics of fuel cell projects. In addition, a comparative analysis with competing CHP technologies (internal combustion engines) is covered. Results show that fuel cells are becoming financially competitive although combustion engines are still a more viable option. For large-size supermarkets the payback time for installing a fuel cell system is 4.7-5.6 years versus 3.6-5.6 years for internal combustion engines. The work also discusses the prospects of fuel cells under different market and policy scenarios as well as technological improvements; thus, offering insights in what are the key aspects which can foster fuel cell installations.

INTRODUCTION

Small scale CHP units (< 1 MW_{el}) are increasingly being installed in distributed energy applications across a wide range of buildings and urban centers (DUKES 2017). The possibility to co-produce heat and power and achieve security of supply is an appealing option for organizations in an ever more unstable energy market. By far, the main type of CHP unit installed is internal combustion engines (ICE), usually fueled by natural gas. Another alternative to combustion engines is the natural gas-powered fuel cell (FC). FCs have some benefits over combustion engines, primarily higher efficiencies, but have not seen widespread use due to high capital costs. Nevertheless, recent reports suggest FCs are increasingly being deployed in several applications; such as supermarkets (Benjamin 2017). Moreover, recent studies have shown that the economics of FC projects are improving (McLarty 2016). As several factors need to be considered when conducting a techno-economic analysis (such as space constraints, installation costs, and energy costings), most of the literature focuses on analyzing a specific building or application. Therefore, it is difficult to extrapolate and give an exhaustive answer on the current applicability of FCs to a specific sector. In addition, comparative analyses with competing technologies, such as internal combustion engines, have seldom been taken into consideration. These analyses are important to understand the economic feasibility of a technology, as decision makers will consider the full range of competing technologies before conducting an investment. This study proposes to comprehensively analyze the techno-economic performance of FCs in food retail buildings. Several supermarkets of distinct size and characteristics were assessed contrasting the performance of FC vs. ICE CHPs. The driving rationale behind this analysis is to highlight the benefits and challenges faced by FCs technology in commercial sites.

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CASE STUDIES AND DATA COLLECTION

Supermarkets data

Food retail buildings present a high variability in size, ranging from convenience stores (sales area < 10,000 ft^2) to large supermarkets (sales area > 40,000 ft^2). Large stores in southern England consume around 4 GWh of electricity and 2 GWh of heating annually. In general, large stores are better suited for a CHP system than smaller stores as these consume more energy and have high energy bills. Large CHP units can then benefit from economies of scale offering a lower cost per kW_{el} produced, which makes the investment more attractive. In this work, 14 large stores (sales area > 40,000 ft2) were selected for the case study. As an example, energy attributes of a typical site are shown in Table 1.

Stores and demand data. 1-year worth of historical data related to the electrical and heating demand were gathered for each store considered. The data was made up in half-hourly (HH) intervals and was post-processed to account for missing values. The load data presents daily and seasonal variations with the heating demand fluctuating mostly in winter and the electrical demand in the summer (when the efficiency of the refrigeration system is highly dependent on external temperature). Fig. 1 shows 1-week worth of HH data during the winter period.

Table 1. Key indicators for a typical large supermarket.

Peak/average electricity load	Annual electricity demand	Peak/average heat load	Annual heat demand	Heat-to-Power ratio	Annual operating costs
645/494 kW	4.37 GWh	619/217 kW	1.894 GWh	0.43	£ 466k

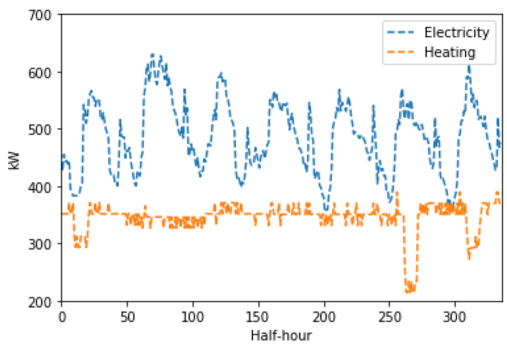

Figure 1. Heating and electricity demand profiles for a typical case study over 1 week.

Utility prices. Like the demand data, HH price data was collected for each supermarket. The price of utilities, especially electricity, is strongly affected by the network charges and government tariffs. The methodology used to calculate price data considers the variability of these tariffs with time and location in the UK and has been described by (Soler et al. 2017). For example, electricity prices are very volatile through the day ranging from 7 p/kWh to more than 30 p/kWh during peak hours. How these variations interact with the electrical and heating demand strongly impacts the economics of CHP investments. 2016-2017 UK data were used to quantify the HH price variation over the annual mean. Unless otherwise specified, the annual price mean used was 11.9 p/kWh for electricity and 2.48 p/kWh for gas.

Policies. UK government policies can have a significant impact on low carbon investments by offering tax reduction and incentives. With respect to CHP installations, the current policy is dependent on the unit running efficiently according to the CHP quality index (CHPQI). If this indicator is met (e.g. higher than 105 in the first year of operation) then benefits apply. The benefits considered for this study were: 1) enhanced capital allowance (ECA), which entails a capital cost discount on the CHP equal to the corporate tax discount (taken in this study as 26%) and 2) carbon climate levy (CCL) exemption, which allows to exclude the CCL tax from the cost of natural gas.

Investment cost. Apart from the unit price, many other factors affect the cost of the investment. In particular, when considering a CHP project, it is very important to consider the installation costs. These costs can include the installation of a gas connection to the CHP, the space preparation and builders' work, upgrade of the heating system, etc., and can be of the order of £ 250k-450k for large stores. These costs vary significantly from case to case and generally increase with the area of the stores. The installation costs used in this study are reported in the Appendix table. As shown in the next section, these costs can impact noticeably the feasibility of CHP projects.

FC data

Technical data for a phosphoric acid FC was gathered from a manufacturing company and is detailed in Table 2 along with the data of a standard ICE CHP unit for comparison. The values reported are for full load operation.

Table 2. Technical data for a commercial FC unit and an ICE CHP of similar size.

Unit	Electrical efficiency (LHV)	Thermal efficiency	Parasitic load	Minimum part load	Lifetime
Phosphoric acid FC	45%	46%	0%	10%	20 years
ICE of equivalent size	39%	45%	2%	40%	20 years

The efficiency values reported in Table 2 are reported using the gas lower heating value (LHV) as commonly found in CHP technical data. However, gas metering is usually based on gas higher heating values (HHV). Therefore, to calculate the electricity produced, the LHV efficiency was converted to the (lower) HHV efficiency by multiplying for the corresponding heating value ratio (= 36/39.8). Both the values of the thermal and electrical efficiency are reported assuming full load operation. At part load the efficiency can change considerably. For the FC model considered in Table 2, it slightly increases up to 46% at 60% part load, then drops to 39% at 50% part load, and then decreases linearly to 10% at 10% part load. For this study, the efficiency vs. part load operation curves provided by the manufacturer were used (Doosan 2017). The unit lifetime of 20 years reported in Table 2 includes a FC stack replacement at year 10. Nominal capital costs for FC and ICE CHP were taken respectively as £2,600/kW and £826/kW. Note that in the case of FC a 26% capital discount due to the CHPQI policy being met bringing the unit capital cost down to £1,924/kWh. The maintenance costs were gathered from CHP manufacturers and taken as 0.02 p/kWh per electricity produced. This value includes the FC stack replacement at year 10 and the ICE major overhaul at year 10.

ASSESSMENT METHOD

Techno-economic model

To simulate the performance of CHP units in supermarkets, a techno-economic optimization model was adopted. The basis is the "TSO model" which has been described in detail in previous publications (Cedillos et al. 2016, Acha et al. 2018). The model takes store and technology data as input and finds the optimal unit size and control strategy to maximize the cost savings. In this work, the objective function chosen was the cumulative discounted cash flow of the investment over the lifetime of the technology (using a 9% discount rate). Carbon savings are considered when evaluating the economics of CHP solutions in terms of carbon reduction commitment (CRC) costs. The results presented in this study assumes the existence of an optimal control system. Other sub-optimal control strategies (e.g. load follow) result in an economic performance which is worse than the one reported in this study. Unless the CHP control strategy adopted is very inefficient, the differences in savings between an optimized strategy and load following are not more than 20%, which results in longer payback periods by about 0.5-1.5 years.

Key financial indicators

The KPIs used in this study to assess the performance of CHP investments are 1) the simple payback time of the investment and 2) its internal rate of return. The payback time was chosen as it is a straightforward indicator and a very common metric. However, in case of low carbon investment, simple payback it is restrictive and does not offer a long term view on the investment. This is particularly true for projects with long lifetime and high capital cost (such as FC). The internal rate of return (irr) provides this foresight and was therefore also adopted, as defined implicitly by:

$$0 = \sum_{t=1}^{T} \frac{C_t}{(1 + irr)^t} - C_0 ,$$

where Ct is the net cash inflow during the period t, and C_0 is the total investment cost. It is worth noting that the *irr* is only slightly dependent on the lifetime of the project as any cash inflow after 15-20 years will be significantly discounted and will not affect the economics of the project. Both the payback time and the *irr* were calculated by considering an average annual electricity price over the project lifetime (11.9 p/kWh for electricity and 2.48 p/kWh for gas unless otherwise specified). Even if this approach is not realistic as electricity prices change over the year, it is straightforward to understand and does not involve choosing arbitrary inflation rates for the utilities. As mentioned in the previous section, the seasonal and daily volatility of the price were however captured by imposing to the average price a similar volatility as the historical half-hour utility profiles (Soler et al. 2017).

RESULTS AND DISCUSSION

A case study in detail

The results of a particular case study are first discussed in detail to offer a clear understanding of the present analysis. The model described in the previous section was applied to simulate the techno-economic performance of a FC unit in the supermarket described in Table 1, which represents a typical case of a large supermarket (sales area of 87,000 ft^2). The performance of a standard ICE CHP, of roughly the same capacity, is also reported along the results of the FC for comparison. In this case, a 460 kW_{el} FC CHP unit and a 500 kW_{el} ICE CHP were chosen as optimal solutions.

The optimal operational schedule of the FC is reported in Fig. 2 for one week in January. As shown, the strategy for the winter period is to cover all the heating demand and partially the electrical demand, and ramp up to full load in those periods of the week when the electricity price is particularly high (usually between 17.00 and 19.00 pm). In this particular case, the difference in savings between an optimized operation (such as the ones reported in Fig. 2) and a standard operation (such as electricity load following during store running hours) is £ 53,000 per year; representing approximately 20% of the annual savings.

Fig. 3 shows the not-discounted project cash flow of the investment for FC CHP and ICE CHP, for both cases when policies are considered and when they are not. As indicated, the cash flow of both technologies looks attractive. In the case where policies are not included the ICE CHPs has a payback time significantly lower than FC (2 years). In the case where policies are considered, the difference in payback time is reduced to 1.4 years. In this scenario, the payback time when policies are included is less than 5 years while the *irr* is 24%, which are both reasonably attractive for such an investment. If policies are not included, the payback time would increase to 6.4 years. If, on top of that, optimized controls were not available the payback time would further increase to 7.8 years. A condition that would make such a project unviable.

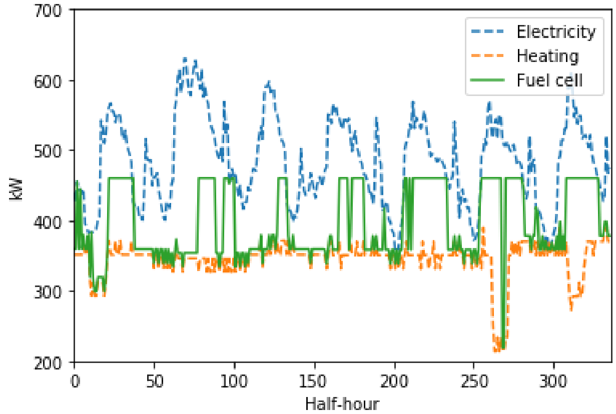

Figure 1. Simulated operation of a 460 kW_{el} fuel cell into a large supermarket along with the heating and electrical demand of the store for a week in January.

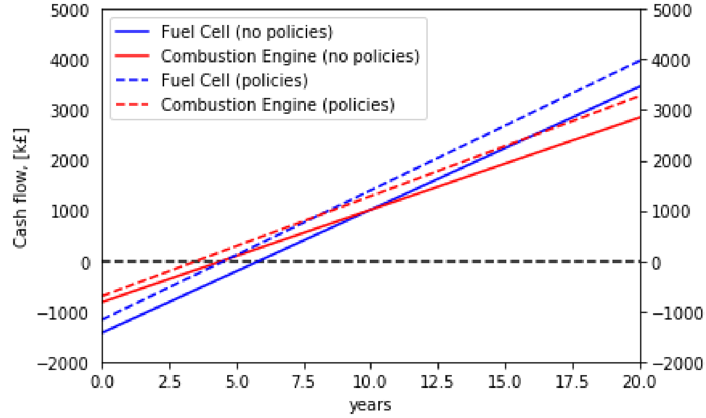

Figure 3. Cash flow of 460 kW_{el} fuel cell and 500 kW_{el} internal combustion engine CHP installation into a large supermarket considering or not the presence of policies: enhanced capital allowance (ECA) and climate change levy (CCL) exemption.

Multi-site case study

The methodology utilized in the previous section was applied to 14 supermarkets. Fig. 4 shows the expected payback time for a FC and ICE CHP investment in different stores in the UK, considering all the possible factors affecting the project (*e.g.* project investment costs, policies, etc.). The payback of FCs is found to be between 4.6 and 5.6 years; ICE CHP have, on average, a payback time 6 months shorter than FC, ranging between 3.6 and 5.6 years. The *irr* shown by Fig. 5 also follows a similar trend, being around 24% for FCs and ranging from 21% to 36% for ICE CHP. Generally speaking, the higher cost of FC units is offset by their higher efficiency, which results in greater savings per year. However, the main factor which reduces the economic gap between FC CHP and ICE CHP is the presence of project installation costs. These costs play a significant role as they have to be included even in the installation of a very cheap CHP system. In the case of ICE, installation costs can represent 50% of the total investment cost. Therefore they almost double the investment cost that would otherwise be paid if only the capital cost of the unit was considered.

An interesting point identified is that the outcome of FC investments was similar for each case, whilst ICE exhibited some very low payback (case 2) as well as sometimes paybacks higher than FC (case 8). Upon investigation, the reason for the higher volatility in the ICE CHP results was found to be linked to the heating demand of the building. The lower efficiency of ICE CHP means that the savings from electricity generation are not enough to build a solid economic case as the savings from heat cogeneration play a significant role. These savings are mainly related to the heating demand of the building which is quite distinct between each supermarket. The FCs, on the other hand, make most of their savings from displacement of imported electricity and are less related to the variable heating demand of the building. It is also important to discuss the effect that current UK policies have on these CHP projects. The high efficiency of FCs allows the unit to easily meet the CHPQI threshold and therefore achieve benefits on ECA; such a benefit is key to make the investment viable. Without such benefits the payback time would increase by about 1.6 years. ICE CHPs are less dependent on the policy due to their lower capital cost as they exhibit a 1 year penalty payback when policies are not included. Albeit, ICE CHPs do not always meet the CHPQI threshold and the application of policies benefits is not granted. In the case studies analyzed for this work, 50% of the CHP units met the CHPQI threshold.

Overall, it appears that FC present reasonable payback time and good *irr* values, which makes them attractive as a low carbon investment. However, competitive ICE technology hampers the widespread installation of FC CHPs. The situation could change in the future as a result of technological development or change in market conditions.

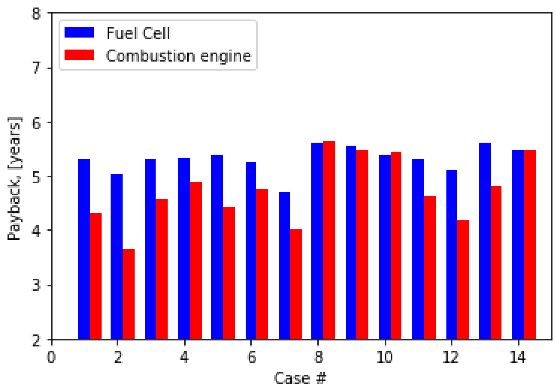

Figure 4. Simulated payback time of fuel cell and internal combustion engine CHP investment into large supermarkets.

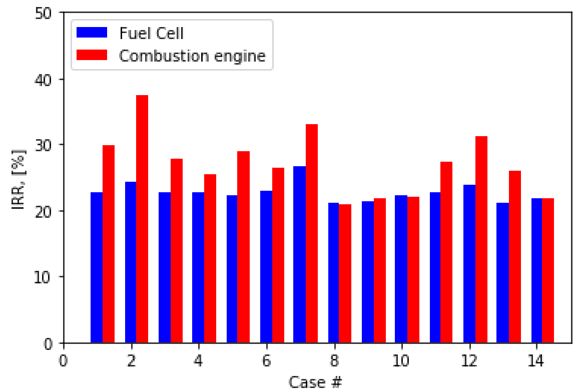

Figure 5. Simulated internal rate of return (*irr*) of fuel cell and internal combustion engine CHP investment into large supermarkets.

Sensitivity analysis

In this section a sensitivity analysis was conducted over different parameters to understand the key variables affecting FC investments and their prospects in possible future scenarios. Fig. 6 and Fig. 7 report the variation in annual savings and payback time as a function of the gas and electricity prices, which are the main factors affecting a CHP investment. The results reported in these figures belong to case 2. As shown by Fig. 7, when the electricity price is high (>18p/kWh), the gas price doesn't affect significantly the economics of the investment. The reason is that the big spread between the values of the two commodities makes gas a low-value commodity and therefore less influential on the overall project viability. As electricity is expected to considerably increase over the next 20 years (up to 100% in according to BEIS, 2017), it is possible to consider a scenario where the electricity price hits 15 p/kWh and the gas price remains stable to around 2.5 p/kWh resulting in a competitive 3 years payback time for the FC unit. It is however important to assess how FC will perform against competitive CHP alternatives under different energy scenarios.

Fig. 8 shows the payback time contour lines as a function of gas and electricity price for respectively ICE (blue) and FC (black) CHPs. As the figure shows, the ICE CHP always presents lower payback than the FC unit for all values of gas and electricity price. The difference between the two technologies decreases at higher gas prices as fuel utilization efficiency becomes an increasingly important factor and FCs are better have an edge on CHPs in this respect. From this analysis, it follows that changes in the energy market alone are not enough to allow FCs to become an appealing alternative to standard CHP systems for the food retail sector. It seems that for FC to be widely adopted there must be a technological development or capital cost reduction. It is reasonable to expect such developments to occur for FCs due to the research and development effort taking place in this field. On the other hand, ICE technology is quite mature there is small room for improvement.

To understand what are the key factors driving FC competitiveness, Fig. 9 offers the results of the sensitivity analysis conducted on an increase in FC efficiency and a decrease in FC capital cost. As shown, an increase in efficiency does not play a significant role in affecting the economics of FCs despite higher efficiencies implying that less fuel (natural gas) is used to power the unit. However, the efficiency of FC is high enough to make fuel consumption not influence the investment. On the other hand, a reduction in capital cost significantly decreases the payback time. Capital cost reduction should therefore be the focus of research and development in the field of FC design.

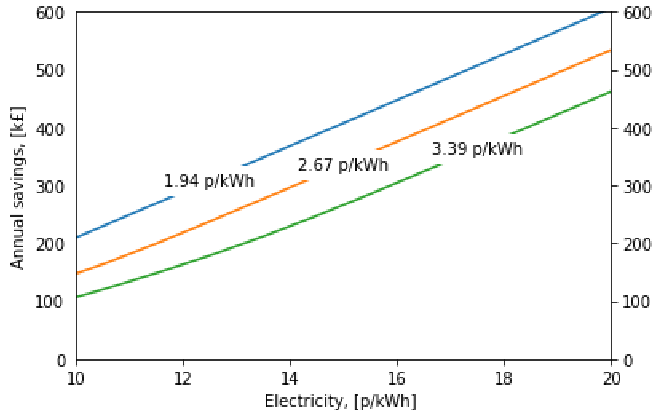

Figure 6. Simulated annual savings of a 460 kW_{el} fuel cell unit into a large supermarket as a function of the electricity price and gas price.

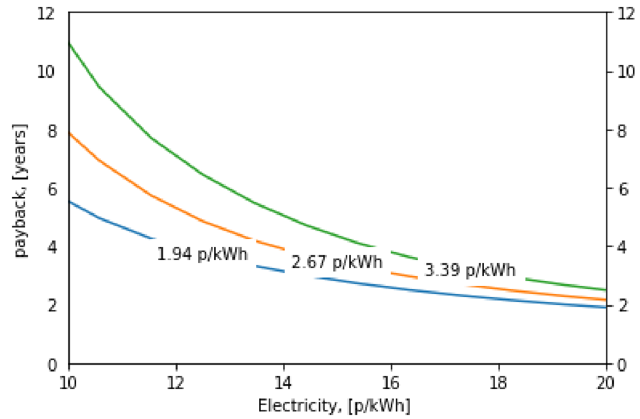

Figure 7. Simulated payback of a 460 kW_{el} fuel cell unit into a large supermarket as a function of the electricity price and gas price.

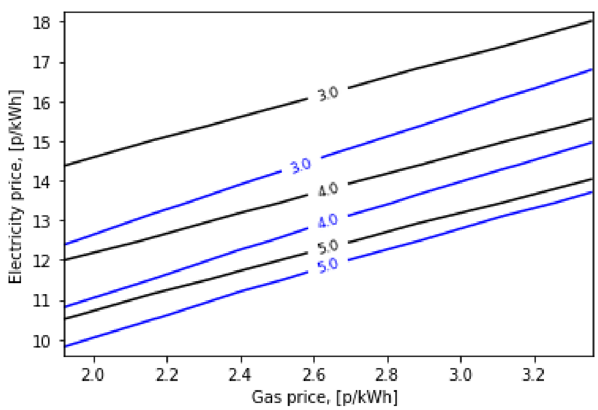

Figure 8. Simulated payback regions of a 460 kW_{el} fuel cell (black lines) and corresponding 500 kW_{el} internal combustion engine (blue lines) CHPs into a large supermarket as a function of the electricity price and gas price.

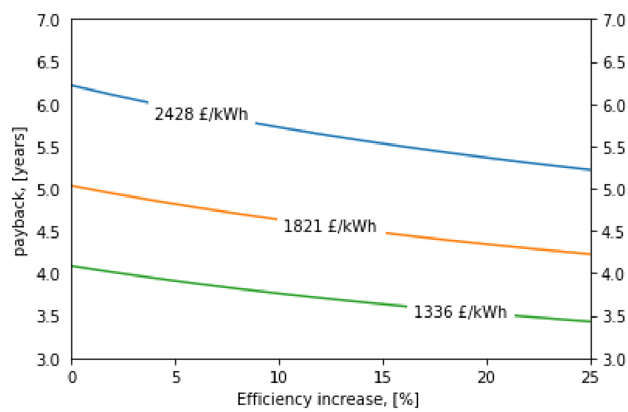

Figure 9. Simulated payback of a 460 kW_{el} fuel cell into a large supermarket as a function of increase in electrical efficiency and capital cost.

CONCLUSION

A techno-economic study was conducted simulating the performance of FCs into 14 large supermarkets with the intention of understanding the key factors affecting FC competitiveness. The FC technology was contrasted against ICE CHP units to understand the performance gap that could increase the uptake of FC projects. The results of the research show that:

- FCs have become increasingly competitive for large supermarkets obtaining a range of payback time between 4.7-5.6 years with an 21-27% internal rate of return;
- FC CHPs present payback times around 6 months higher than internal combustion engine CHPs. The main aspects causing such relatively small gaps, notwithstanding the large difference in capital cost, were found to be: 1) FC efficiency; 2) installation costs; 3) government policies;
- An increase in electricity prices will decrease the payback time of FC. By using the utility price projections, in the next 5 years, the payback of installed FCs will be around 3-4 years for larger stores. However, internal

combustion engine CHP will always be slightly more economical for the range of utility variation considered due as high electricity prices drive most of the savings;

- A technological improvement or cost reduction seems therefore needed for FCs to achieve better competitiveness than internal combustion engines;
- Efforts in FC development should be devoted in decreasing capital cost rather than improving efficiency as this latter factor was shown not to have a significant impact on the economics.

ACKNOWLEDGEMENTS

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ABBREVIATION

CCL	=	Climate Change Levy
CHP	=	Combined Heat and Power
CHPQI	=	Combined Heat and Power Quality Index
CRC	=	Carbon Reduction Commitment
FC	=	Fuel Cell
HVAC	=	Heating, Ventilation and Air Conditioning
HH	=	Half-hourly
HHV	=	Higher Heating Value
ICE	=	Internal Combustion Engine
LHV	=	Lower Heating Value

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APPENDIX

Table 1A. Simulation results of fuel cell CHPs deployed in different supermarkets.

Case study	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Store annual electrical demand [MWh]	3138	4527	2891	2610	2946	2544	2563	2059	2110	1857	2695	2942	2615	1931
Store annual thermal demand [MWh]	2335	2381	1567	1600	2030	1451	1950	1705	1416	2014	2027	1315	1143	1066
FC unit [kW_{el}]	400	460	360	320	400	320	340	260	280	260	340	380	360	260
Investment [k£]	1111	1259	977	897	1112	898	937	769	816	765	941	1032	951	760
Annual savings [k£]	209	250	184	168	206	171	199	137	147	142	178	202	170	138
Payback time [years] (without policies)	5.3 (6.9)	5.0 (6.6)	5.3 (7.0)	5.3 (6.9)	5.4 (7.0)	5.3 (6.8)	4.7 (6.1)	5.6 (7.2)	5.5 (7.2)	5.4 (6.9)	5.3 (6.9)	5.1 (6.7)	5.6 (7.4)	5.5 (7.1)
Internal rate of return (without policies)	23% (16%)	24% (17%)	23% (16%)	23% (16%)	22% (16%)	23% (16%)	27% (19%)	21% (15%)	21% (15%)	22% (16%)	23% (16%)	24% (17%)	21% (14%)	22% (15%)
FC- natural gas consumed [MWh]	7153	9337	6580	5761	6926	5826	6098	4667	4869	4513	6115	6793	6123	4434
FC- electricity produced [MWh]	2991	3904	2752	2409	2896	2436	2550	1952	2036	1887	2557	2841	2560	1854
FC- electricity exported [MWh]	25	2	15	14	21	12	38	12	22	63	8	19	14	17
FC- annual utilization	85%	97%	87%	86%	82%	87%	85%	85%	83%	83%	86%	85%	81%	81%
ICE CHP payback time [years] (without policies)	4.3 (5.3)	3.6 (4.6)	4.6 (5.7)	4.9 (6.1)	4.4 (5.4)	4.7 (5.9)	4.0 (4.9)	5.6 (7.0)	5.5 (6.7)	5.4 (6.7)	4.6 (5.7)	4.2 (5.2)	4.8 (6.0)	5.5 (6.7)
ICE CHP	108	105	102	100	105	100	105	106	100	109	106	97	96	97