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Optimal Design and Operation of a PEMFC-based CHP System Connected to Grid

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Abstract. This paper is focused on the optimal design and operation of a Combined Heat and Power (CHP) system based on Proton Exchange Membrane Fuel Cell (PEMFC) connected to grid, whose aim is to supply the energy requirements of the Educational Complex of the Engineering School of Eibar - University of the Basque Country (UPV / EHU). To achieve the optimal design and operation of the system, the PEMFC-based CHP system has been simulated on the base of each of the proposed schemes and operation strategies, and a detailed analysis of the results obtained has been conducted, which has allowed to choose as optimal, the design that has better maximized the economic-energetic efficiency of the whole system, and has been adjusted better to the viability criteria established.

Key words

PEM Fuel Cell; Combined Heat and Power (CHP); Optimization; Integrated Sizing; Primary Energy Consumption.

1. Introduction

Currently, primary energy consumption in buildings accounts for over a third of the world total energy consumed [1]. This aspect, along with economic progress in emerging countries and the lack of an alternative approach on energy resources, causes its scarcity and price rising, heading towards a future of economic uncertainty and, in consequence, a stagnation in the social model. In this context, there is a need to redesign the energy model in order to substantially improve energy efficiency and curb dependence on external energy resources. Distributed generation based on cogeneration, is presented as a coherent alternative to traditional centralized generation systems by matching the thermal demand to power generation, thereby increasing efficiency in resource consumption and minimizing, as far as possible the environmental impact [2].

Among different technologies that could work in cogeneration, PEMFC is the one that offers greater efficiency, lower noise and greater flexibility in controlling the power generated, compared to internal combustion engines, gas microturbines and Stirling engines [3]. This is why the purpose of this work focuses on the optimal design and operation of a decentralized electric and thermal generation system based on PEMFC, in order to replace the current energy supply system, which is based on the electrical grid and oil-fired boilers.

2. Proposed System

Figure 1 shows the proposed optimization scheme of the PEMFC-based CHP system connected to grid. To supply hydrogen to the PEMFC, has been opted for a steam reforming system of natural gas, because, apart from not requiring an additional cost to the infrastructure for transporting natural gas, it is one of the most developed alternatives, efficient and economic, despite its environmental impact [4].

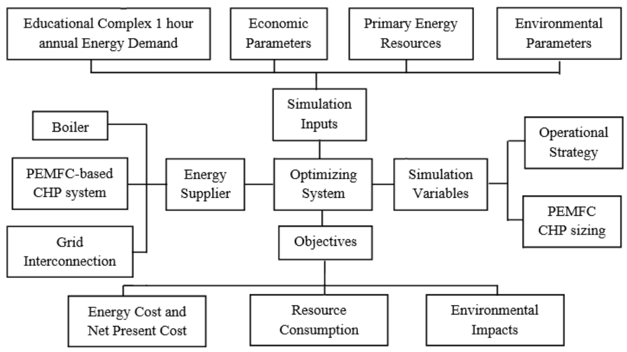

Fig. 1. Proposed optimizing scheme of the PEMFC-based CHP system connected to grid.

Hydrogen produced is stored in a hydrogen tank, whose sizing has been set according to the most efficient hydrogen production and consumption program that has been obtained by system optimization.

Electricity rates are time-based, which plays an important role when setting the optimal schedules of the devices involved in the system. Moreover, it has been considered the possibility of injecting energy into the grid at times of low electrical demand, raising the possibility of implementing in the future an electricity tariff based on net metering. There has also been carried out a thermo-economic study aimed at sizing a thermal storage system to support the oil-fired boilers.

Due to the large thermal demand of the complex in relation to electricity demand, the boiler is needed to support the cogeneration system. In this sense, the energy demand will be supplied by the PEMFC-based CHP system, the boiler and/or the grid.

3. Optimization Methodology

The optimization methodology is based on three main tasks: simulation, optimization and sensitivity analysis.

A. Simulation

During the simulation, starting from the entered scheme and settings, the system is modeled step by step per unit time to determine its behavior and viability annually, depending on all the costs associated with primary energy resources and each system element, efficiency of each device and environmental parameters.

During simulation, it is taken into account the energy demand per unit time and the ability of the system to supply that demand. In this sense, energy flows between components are calculated in order to decide their behavior depending on whether exists or not excess or deficit of power generation by the PEMFC-based CHP system. As long as system constraints do not indicate otherwise, the demand will be supplied from the power source that involves the cheapest cost of generation.

The PEMFC system will come into operation whenever the inequality (1) is met, otherwise the electrical and thermal demand will be supplied by the grid and the boiler, respectively.

$$\dot{m}_{H_2}{\cdot}C_{H_2} - S_{R_e}{\cdot}P_{Ex} - P_{T\_fc}{\cdot}C_b < P_{E_d}{\cdot}P_{R_e} + P_{T_d}{\cdot}C_b \quad (1)$$

where $\dot{m}_{H_2}{\cdot}C_{H_2}$ represents the cost (*€/h*) of generating electric power by the PEMFC, being C_{H_2} and $\dot{m}_{H_2}$ the hydrogen price (*€/kg*) and the hydrogen flow rate (*kg/h*), respectively. The term $\dot{m}_{H_2}$ can be calculated from equation (2) given as:

$$\dot{m}_{H_2} = c_0 \cdot P_{ER\_fc} + c_1 \cdot P_{E\_fc} \quad (2)$$

where P_{E_fc} is the available power at terminals of the power inverter of the PEMFC (*kW*), c_0 is the coefficient of interception of the hydrogen consumption curve ($9 \cdot 10^{-4}$ $kg/h/kW_{rated}$), c_1 is the slope of the hydrogen consumption curve (0.06 $kg/h/kW_{output}$) and P_{ER_fc} is the rated electric power of the PEMFC (*kW*).

C_{H_2} can be calculated from equation (3) given as:

$$C_{H_2} = \frac{C_{NG}}{\eta_R} \quad (3)$$

where C_{NG} is the natural gas cost (*€/kg*) *and* η_R is the reformer efficiency (0.8).

The second term of the inequality (1) $S_{R_e}{\cdot}P_{Ex}$, represents the revenue (*€/h*) achieved by selling the excess of electric power generated by the PEMFC P_{Ex} (*kW*) at a sellback rate S_{R_e} (*€/kWh*). P_{Ex} can be calculated from equation (4) given as:

$$P_{Ex} = P_{E\_fc} - P_{E_d} \quad (4)$$

where P_{E_d} is the electric power demand (*kW*).

When P_{Ex} is negative, the grid will supply that deficit of power at P_{R_e} purchase rate (*€/kWh*). In case of not existing a net metering tariff, the term P_{Ex} will only take negative values, so that the P_{E_fc} shall be adjusted to P_{E_d} until P_{E_fc} equals the value of P_{ER_FC}.

The third term of the inequality (1) $P_{T\_fc}{\cdot}C_b$, represents the cost (*€/h*) that would suppose producing the thermal power generated by the PEMFC P_{T_fc} (*kW*) when it is generating P_{E_fc}, in case this thermal power were generated by the boiler, being C_b (*€/kWh*) the boiler marginal price. P_{T_fc} shall be adjusted to the demand of thermal power P_{T_d} (*kW*) until P_{T_fc} reaches its maximum value, which is when P_{T_fc} equals the value of P_{ER_FC}. From that moment, the entire deficit of thermal power will be supplied by the boiler. P_{T_fc} can be calculated from equation (5) given as:

$$P_{T\_fc} = \left(1 - \eta_{fc}\right) \cdot H_R \cdot \dot{m}_{H_2} \cdot \frac{LHV_{H_2}}{3.6} \quad (5)$$

where H_R is the heat recovery ratio (0.8), LHV_{H_2} is the hydrogen lower heating value (120.21 *MJ/kg*) and η_{fc} is the electrical efficiency of the PEMFC, which can be calculated by equation (6) given as:

$$\eta_{fc} = \frac{3{,}6 \cdot P_{E\_fc}}{\dot{m}_{H_2} \cdot LHV_{H_2}} \quad (6)$$

C_b can be calculated from equation (7) given as:

$$C_b = \frac{3{,}6 \cdot C_{D\_oil}}{\eta_b \cdot LHV_{D\_oil}} \quad (7)$$

where C_{D_oil} is the cost of the diesel oil (*€/kg*), η_b is the efficiency of the boiler (0.8) and LHV_{D_oil} (*43.2 MJ/kg*).

The fourth term of the inequality (1) $P_{E_d}{\cdot}P_{R_e}$, represents the cost (*€/h*) of buying electric power from the grid.

The fifth term of (1) $P_{T_d}{\cdot}C_b$, represents the cost (*€/h*) of generating the thermal power demand P_{T_d} (*kW*) by the boiler.

The diesel oil flow rate $\dot{m}_{D\_oil}$ (*kg/h*) consumed by the boiler can be calculated by equation (9) given as:

$$\dot{m}_{D\_oil} = \frac{3{,}6\cdot\left(P_{T_d} - P_{T\_fc}\right)}{\eta_b \cdot LHV_{D\_oil}} \tag{9}$$

The natural gas flow rate $\dot{m}_{NG}$ (*kg/h*) consumed by the reformer can be calculated by equation (10) given as:

$$\dot{m}_{NG} = \frac{\dot{m}_{H_{2}R}}{\eta_R} \tag{10}$$

where $\dot{m}_{H_{2}R}$ is the hydrogen flow rate (*kg/h*) produced by the reformer.

The level of the hydrogen tank T_L (*kg*) can be calculated by equation (11) given as:

$$T_L = T_0 + \dot{m}_{H_{2}R} \cdot t_R - \dot{m}_{H_2} \cdot t_{fc} \tag{11}$$

where T_0 is the initial level (*kg*) of the hydrogen tank (*full tank*), and t_R and t_{fc} represent the operating time of the reformer and the PEMFC, respectively.

The water tank volume v (m^3) can be obtained from equation (12) given as:

$$v = \frac{3.6\cdot 10^3 \cdot H_{ex\_fc}}{\rho \cdot C_p \cdot (T_{max} - T_{min})} \tag{12}$$

where H_{ex_fc} is the daily average value of the excess of thermal energy (*kWh*) produced by the PEMFC, ρ is the density of the water (1000 kg/m^3), C_p is the specific heat of the water (4.186 MJ/(kg ºC)), T_{max} is the maximum storage temperature (80 ºC), and T_{min} is the minimum storage temperature (20 ºC).

On the basis of equations (1) to (12), the entire system, is simulated hour-by-hour for the lifetime of the system, which in this case it has been 25 years. Through this simulation are obtained the operating hours of each device, the fuel used and the energy generated by the reformer, PEMFC, boiler and also the energy exchanged with the grid. For this, all cost coefficients and electrical and thermal data of the demand are updated hourly throughout the lifetime of the system. This simulation is performed for all possible configurations, taking into account a predefined range of sizes and powers of all system devices, such as flow rate of the reformer, hydrogen tank size, rated power of the PEMFC and the electrical power contracted.

Table I shows the range of power and size taken into account for each device in order to simulate various configurations of the system.

Table I. – Power and size ranges of the system devices taken into account to implement various system configurations.

Element	Range
Power Grid Contracted	185 - 265 kW
PEMFC	0 – 80 kW
Steam Reformer	0 – 5 kg/h
H_2 tank @ 200 bar	0 - 5 kg

The power and size ranges shown in Table I have been stablished taking into account the maximum and average electric power demand of the complex, which are 265 kW and 80,56 kW, respectively. The data obtained from the simulations are processed later in the optimization task.

B. Optimization

Once simulated all possible system configurations, the optimization task allows select the simulation with lowest total net present cost (NPC).

During the optimization task, the non-viable configurations are discarded and viable ones are classified regarding their NPC (€), which is defined by equation (13). In section 4-B are defined all the parameters of the costs taken into account to evaluate (13).

$$NPC = \sum_{i=1}^{n}\left(C_{PV_i} - R_{PV_i}\right) \cdot f_{d_i} \tag{13}$$

Where n are the years of the system lifetime, C_{PV_i} is the present value of all the costs (€) that the system incurs over the year i, R_{PV_i} is the present value of all the revenue (€) that system earns over the year i and f_{d_i} is the discount factor of each i year. C_{PV_i}, R_{PV_i} and f_{d_i} are defined in the equations (14), (15) and (17), respectively.

$$C_{PV_i} = C_{Capital} + C_{O\&M} + C_{fuel} + C_{grid} \tag{14}$$

Where $C_{Capital}$ is the capital cost due to initial capital or equipment replacement; $C_{O\&M}$ is the system operation and maintenance cost, calculated by the sum of the multiplication of the hours of operation of each device by its O&M cost; C_{fuel} is the cost associated with natural gas and it takes into account the variable and fixed cost of the natural gas consumption and its delivery; C_{grid} is the cost associated with buying power from grid and it takes into account the variable and fixed cost of the electricity consumption and power contracted.

$$R_{PV_i} = S_V + G_{Sales} \tag{15}$$

Where S_V is the sum of the salvage value of each component and G_{Sales} is the grid sales revenue. S_V can be calculated from equation (16) given as:

$$S_V = C_{rep} \cdot \frac{R_{lt} - t_O}{R_{lt}} \tag{16}$$

where C_{rep} is the replacement cost of each component, R_{lt} is the lifetime (*h*) of each component and t_O are the hours of operation of each component.

$$f_{d_i} = \frac{1}{(1+r)^i} \tag{17}$$

Where r is the real interest rate (%), which is defined by equation (18) given as:

$$r = \frac{r' - f}{1+f} \tag{18}$$

where r' is the nominal interest rate (%) and f is the annual inflation rate (%).

In order to quantify the cost of power generation of the system for each configuration, it is also calculated the levelized Cost of Energy (COE), which is the average cost per kWh of useful electrical energy produced by the system. The COE can be calculated from equation (19) given as:

$$COE = \frac{C_{T\_ann} - C_b \cdot H_S}{E_S} \tag{19}$$

where C_{T_ann} is the total annualized cost of the system (€), H_S is the total thermal load served (kWh) and E_S is the total electrical load served (kWh). C_{T_ann} can be calculated by equation (20) given as:

$$C_{T\_ann} = C_{RF} \cdot NPC \tag{20}$$

where C_{RF} is the capital recovery factor based on the real interest rate r and the system lifetime years n. C_{RF} can be calculated by equation (21) given as:

$$C_{RF} = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{21}$$

Once having classified the viable solutions with respect to the NPC, the optimal configuration will be that which present a lower NPC, which will allow choosing the optimal size of the PEMFC, reformer, hydrogen tank and the optimal scheduling of the PEMFC that minimizes the total cost of the system throughout its total lifetime. These values are shown in section 5-A and 5-B.

C. *Sensitivity Analysis*

Through sensitivity analysis, simulations with their corresponding optimization based on different configurations and operational strategies are recreated.

It is interesting to analyze the viability that presents the system when it faces to a high degree of independence with respect to the boiler or the grid. In this sense, it has been performed a sensitive study of system behavior, establishing as restriction the minimum fraction of energy produced by the PEMFC f_{min} (%) with respect to the conventional generation, which can be calculated from equation (22) given as:

$$f_{min} = \left(1 - \frac{E_{grid} + H_{boiler}}{E_S + H_S}\right) \cdot 100 \tag{22}$$

where E_{grid} is the total electrical energy consumed from the grid and H_{boiler} is the total thermal energy produced by the boiler.

Given this restriction, there have been studied the system configurations that are able of having a degree of independence of more than 30 % in producing electricity and heat by the PEMFC.

4. Simulation inputs

A. *Energy Demand*

Analyzing the electric bills of three consecutive years, it is found that the electrical demand follows a seasonal pattern. For that reason, the demand is defined in three periods: winter, summer and holiday period. In addition, each period distinguishes weekdays and the weekend. Regarding to the thermal demand, it is previously known the boiler schedule, so that it is set based on that schedule.

Figure 2 and 3 show the seasonal profiles of electrical and thermal demand of the university complex, respectively.

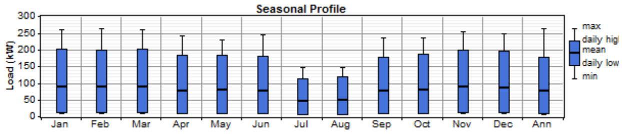

Fig. 2. Seasonal profile of the electrical demand.

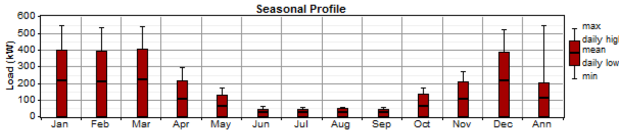

Fig. 3. Seasonal profile of the thermal demand.

B. *Economic Parameters*

The economic parameters are all those costs taken into account when calculating the NPC of each system.

Table II shows the estimated costs per unit of the initial capital, O&M and replacement of each system element. All costs shown in Table II (minus the boiler ones), have been estimated based on an estimate budget given by Ballard Power Systems [5]. These costs are used for simulation and calculation of the NPC, for each possible configuration, taking into account the power and size ranges defined in Table I.

Table II. – Initial capital, O&M and replacement costs of each element of the system.

Element	$C_{initial}$	C_{rep}	$C_{O\&M}$
PEMFC	1,650 €/kW	1,650 €/kW	0.3 €//kW/year
Cooling system	930 €/kW$_{pemfc}$	-	0.06 €//kW$_{pemfc}$/year
Power Inverter	790 €/kW$_{pemfc}$	790 €/kW$_{pemfc}$	2 €/kW$_{pemfc}$/year
Steam Reformer	11,000 €/kg/h	-	44 €/kg/h/year
H_2 storage system	63 €/kg	-	0.44 €/kg/year
Diesel oil Boiler	-	-	1,472 €/year

Some of the replacement costs are not provided, which means that these devices are not replaced during the lifetime of the system. Regarding to the boiler, it has not been taken into account its initial capital, since it is a device already installed. However, apart from its variable costs, there have been also taken into account its fixed costs, such as routine maintenance, amounting to a total of 1918.6 *€/year*.

Table III shows the costs associated with fossil fuel resources, such as natural gas and diesel oil.

Table III. – Costs associated with fossil resources.

Element	Variable term (€/kg)	Fixed term (€/year)
Natural Gas	0.3684 (C_{NG})	473.22
Diesel oil	0.7568 (C_{D_oil})	-

In Table IV the costs associated with the electrical energy are shown. The electricity rates are time-based, in which three periods are distinguished: peak, shoulder and peak-off. Therefore, it is taken into account the variable price and the fixed price for each period.

Table IV. – Costs associated with electrical energy.

Rate	Purchase rate S_{R_e} (€/kWh)	Sellback rate P_{R_e} (€/kWh)	Fixed term (€/kW/month)
Peak-off	0.116	0.116	0.423
Shoulder	0.160	0.160	1.846
Peak	0.179	0.179	2.993

Figure 4 shows the electricity rate schedule used when applying the rates to consumed or injected energy.

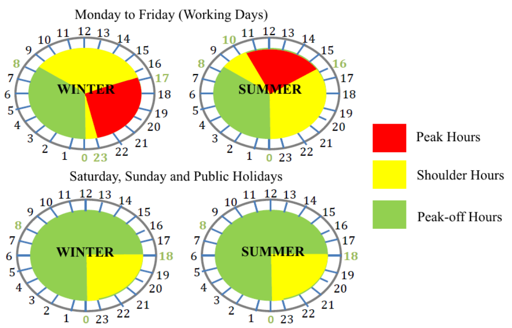

Fig. 4. Electricity rate schedule.

Regarding the nominal interest rate r' and inflation f, there have been taken the values of 5.7% and 1.88%, respectively. Inflation has been calculated as the average inflation in Spain of the period 2006-2014 [6].

C. Durability Parameters

The durability parameters are used to determine when an element of the system must be replaced. In that sense, the PEMFC and the power inverter lifetimes have been set to 40,000 hours and 15 years, respectively. For other elements, the lifetime is not defined since it is supposed that they have a lifetime equal or greater to the system lifetime.

D. Environmental Parameters

Environmental parameters are used to quantify the total emissions of the system throughout its lifetime. In this sense, CO_2 emissions from the grid are estimated at 632 *g* per *kWh* consumed and from the boiler at 270 *g* per *kWh* of thermal energy produced. Considering that in the reforming process are produced from 0.35 to 0.42 m^3 of CO_2 per m^3 of H_2, the emissions from reformer are estimated at 447.7 *g* of CO_2 per *kWh* of electricity produced by the PEMFC [7].

5. Optimized System

A. Optimal System Sizing

Table V shows the optimal design obtained for each element forming the PEMFC-based CHP system after constructing the electricity and heat hourly demand curves, from the average consumption data for three years, and applying the optimization strategies on the proposed scheme.

Table V. – Optimal sizing of each element of the system.

Element	Optimal sizing without net-metering	Optimal Sizing with net-metering
Power Grid Contracted	225 *kW*	225 *kW*
PEM Fuel Cell System	50 *kW*	50 *kW*
Steam Reformer	3.1 *kg/h*	3.1 *kg/h*
H_2 tank @ 200 bar	3.05 *kg*	3.05 *kg*
Thermal Storage Tank	1,675 *L*	3,325 L

On one hand, it can be found that the grid power contracted can be reduced by 11,3 % compared to the current system (*265 kW*), since part of the power is produced by the PEMFC. On the other hand, it can be found that in case of applying the net-metering, the thermal storage need to be oversized compared to the case in which the net metering is not applied.

B. Optimal System Scheduling

The optimal scheduling of the generating devices consists on performing a registration of the output power of each device for each hour of the year from the simulation data of the optimal configuration. Figure 5 and 6 show the optimal scheduling of the PEMFC and the boiler, respectively, without considering the net metering tariff.

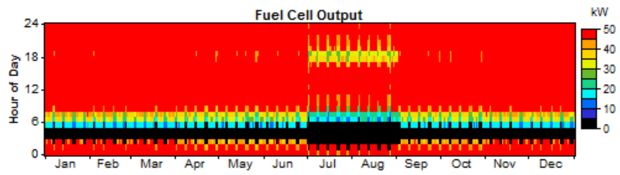

Fig. 5. Optimal scheduling of the PEMFC.

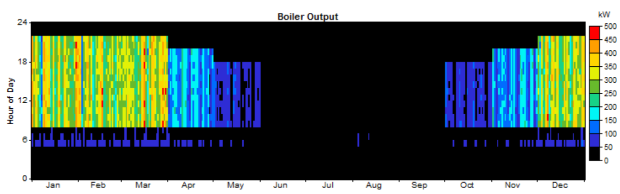

Fig. 6. Optimal scheduling of the boiler.

Comparing Figure 5 to 6, it can be seen that the PEMFC is perfectly complemented by the boiler. In this regard, when inequality (1) is met, all of the thermal energy produced by the PEMFC is intended to supply the heat demand, and when this energy is not enough, it is complemented by the boiler, resulting in increased energy efficiency and lower emissions, since a greater amount of energy is produced from natural gas instead of diesel oil. In figure 5, it can be seen that the PEMFC system works almost all year at nominal power, except several hours during the night when electricity is cheaper and it is worth consuming electric power from grid.

Figure 7 and 8 show the monthly average electric and thermal production, respectively.

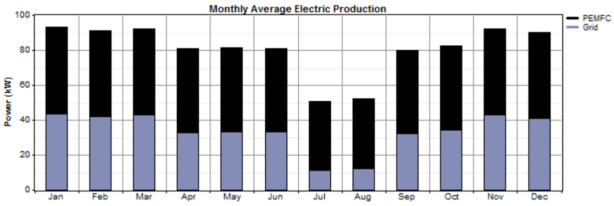

Fig. 7. Monthly average electric production.

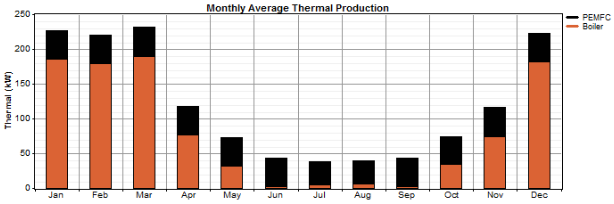

Fig. 8. Monthly average thermal production.

It can be seen that the fraction of the power generated by the PEMFC is higher in the months of July and August, since the average power of the PEMFC is maintained almost all the year at its nominal power while the energetic demand is drastically reduced.

The fraction of electricity and heat generated by the PEMFC with respect to the total generated has been of 36 % without applying the net-metering, and of 41 % when the net-metering has been applied.

6. Optimization Results

Table VI shows a summary of the results for the optimized system, with and without net-metering and the base case, for a 25-year system lifetime.

Table VI. – Comparative summary of the optimized system with and without net-metering and the current supply system.

	COE (€/kWh)	Total NPC (M€)	Diesel Fuel (L/year)	Natural Gas (m^3/year)	CO_2 t/year
Base case system	0.188	4.271	144,983	-	829.33
Optimized system	0.175	4.122	107,224	91,997	503.45
With net-metering	0.161	4.046	103,570	99,746	474.49

It can be observed that in the optimal configuration obtained for the case in which it is not taken into account the net-metering, savings achieved are approximately € 149,000 compared to the base case in which the thermal and electrical load are supplied only by the grid and the boiler, while considering the net metering, the savings amounts to € 225,000. The minimum *NPC* is obtained for the configuration in which the PEMFC has a power of 50 *kW*, resulting in a *COE* of 0.175 € / *kWh* without net metering and 0.161 € / *kWh* with net metering.

Regarding CO_2 emissions, with the optimal configuration and without applying the net metering, it is achieved a 39.29 % reduction in CO_2 emissions, while if the net metering is applied, a 42.78 % reduction in CO_2 emissions could be achieved.

7. Conclusions

This paper has presented the optimal design and operation of a PEMFC-based CHP system connected to grid to supply the energy requirements of the Educational Complex of the Engineering School of Eibar - University of the Basque Country (UPV / EHU). It has been shown the methodology carried out for this purpose and it has been evaluated the possibility of implementing the system through a comparison between the most viable configurations designed and the currently used energy supply system, which is based on grid and oil-fired boilers. The criteria for this comparison have been formulated on the basis of their economic viability, environmental impact, degree of independence and social contribution.

The result of the optimal design and operation of the proposed system has proven to be a viable alternative in terms of economics and harmful emissions, resulting in a saving of 5,969 € per year and avoiding the emission of 326 tons of CO_2 per year, compared to the current supply system. In addition, it have been found that these results are substantially improved if a net metering tariff is applied. The methodology developed to optimize this distributed generation system could be used to achieve an optimal design and operation of any other PEMFC-based CHP system with similar energy requirements.

Ultimately, it can be said that this change of model requires a large initial capital outlay. However, a noticeable drop occurs in the cost of energy, which in turn produces the return on investment in the long-term.

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