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High-temperature fuel cells for fresh water production

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Abstract

This paper analyzes different configurations in which fuel cells provide electricity to a reverse osmosis (RO) desalination plant, and heat is recovered via a heat exchanger pre-heating the input seawater to feed both a multistage flash (MSF) unit and a RO unit. The energetic and economic results of different hybrid configurations with molten carbonate and solid oxide fuel cells are studied and compared. Depending on the efficiency of the different parts of the fuel cell (FC) system, the fuel utilization, the type and size of fuel cell, the internal configuration of the fuel cell stack, the integration of the internal processes in the FC plant as well as the integration of the fuel cell with the desalination technologies, the amount of generated power and heat will significantly vary. Among the different possibilities of integration the scheme of preheating feed water to RO membranes, in order to improve its productivity, or alternatively, reduce the HP pump consumption are particularly interesting.

Keywords: Fuel cell, Desalination; Multistage flash; Reverse osmosis; Combined production of water and energy; Process integration

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1. Introduction

Both drinking water and electricity are essential components for the ordinary operation of the present society system. The combined effect of climate and demographic pressure over the last 50 years has generated potable water and energy scarcity in different regions of the world. In the light of available data, this increasing trend in the water and energy demand will continue in the future [1].

Due to the water shortages, desalination technology has reached great importance as a solution for potable water generation. However, one of their more significant drawbacks is the high power consumption and the environmental load associated to the production of electricity. For this reason co-generation is a very interesting technique to minimize

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this environmental impact. The so-called dual-purpose plants generate power and potable water making use of both electricity and heat released in a power plant or any other power generator. The most relevant advantages of this kind of technique are: the increase of efficiency, the fuel utilization and the optimization of the costs of desalted water. Around a 50% of this cost is directly related to the cost of energy consumed in the process [2].

High temperature fuel cells are suitable technologies for cogeneration. They produce electricity in a cleaner and more efficient way than conventional technologies and the temperature of the flue gases is high enough to produce high-temperature steam. Molten Carbonate Fuel Cells (MCFC) and Solid Oxides Fuel Cells (SOFC) are very suitable fuel cells technologies for cogeneration of heat and power due to their significantly high operating temperatures, 650°C and 900°C respectively. Other fuel cells configurations operate at less than 250°C (sensible heat), therefore the potential for pre-heating fed brine to be used in a profitable way in thermal desalination processes, e.g. Multi-Stage Flash Distillation, is significantly lower.

Some advantages of running dual-purpose power and water plants with fuel cells are

- Higher electrical efficiency and higher overall efficiency (cogeneration).
- Distributed power/water generation.
- No use of oils and lubricants (no mechanical parts included), which are water pollutants.
- Environmental advantages presented by FC vs. conventional power plants.

There are many different possibilities to fuel the fuel cell systems. The easiest way is fueling with natural gas because it is constantly available, it has a high calorific value, its properties are commonly uniform, the pollutants present in the gas are well-known and the cleaning system required is not very complex. Other fuels tested in fuel cell systems are landfill gas, syngas from biomass gasifiers and bio-gas from anaerobic digesters in wastewater treatment plants. These alternative fuels are produced from different types of wastes reducing the consumption of fossil fuels.

In this paper, energy and economical analysis of a molten carbonate and a solid oxide fuel cell co-generation systems applied to different desalination technologies are presented and compared. Al-Hallaj et al. [3] presented a 5.61% of global system efficiency improvement considering the energy savings in a dual-purpose plants consisting of a molten carbonate fuel cell integrated with a MSF desalination plant at Azzour power plant (Kuwait). However, in this work RO technology has been taken because these systems are prevailing over any other desalination system (the global energy efficiency of the dual-purpose plant is 78% and 85% for molten carbonate and solid oxide fuel cell respectively).

The economical analysis compares the viability of the project under the present situation (investment costs of the fuel cells) with the viability in a future scenario (target investment costs). It also compares the economical viability depending on the type of fuel cell. Proposals of using alternative fuels are also studied considering the costs associated to the required cleaning systems and the decrease in the cost of the fuel.

2. Fuel cell systems

Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. As other electrochemical devices, fuel cells are not limited by the Carnot efficiency. The structure of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side. As Fig. 1 shows, gaseous fuels are fed continuously to the anode

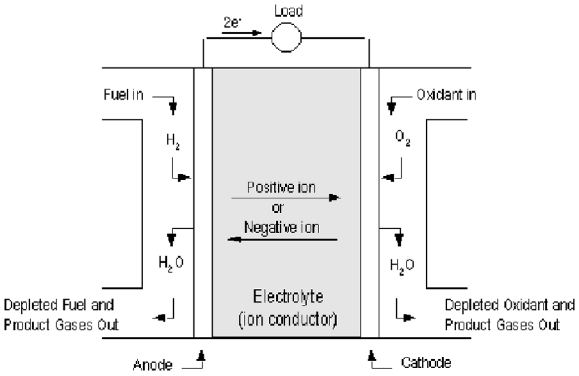

Fig. 1. Diagram of a single fuel cell [4].

and an oxidant is fed continuously to the cathode; the electrochemical reactions take place at the electrodes to produce an electric current.

The fuel or oxidant gases flow through the surface of the anode or cathode and generate electrical energy by the electrochemical oxidation of fuel, usually hydrogen, and the electrochemical reduction of the oxidant, usually oxygen. The electrolyte transports both dissolved reactants to the electrode and conducts ionic charge between the electrodes completing the electric circuit.

The most common classification is by the type of electrolyte used in the cells:
1) Polymer Electrolyte Fuel Cell (PEFC): Temperature is usually less than 120°C. CO is a poison at low temperature. High catalyst loading (Pt) is required in anode and cathode.
2) Alkaline Fuel Cell (AFC): Electrolyte is concentrated KOH at high temperature (250°C) and less concentrated at lower temperature (<120°C). Wide range of electro-catalysts is suitable. CO and CO_2 alter the electrolyte.
3) Phosphoric Acid Fuel Cell (PAFC): Electrolyte is 100% phosphoric. It operates from 150°C to 220°C. Electro-catalyst in both anode and cathode is Pt.
4) Molten Carbonate Fuel Cell (MCFC): Electrolyte is a combination of alkali. It operates from 600 to 700°C. Ni and nickel oxide are adequate to promote reaction.
5) Solid Oxide Fuel Cell (SOFC): Electrolyte is a solid, nonporous metal oxide. The cell operates in the range from 650°C to 1000°C.

Because fuel cells operate at nearly constant efficiency, independent of size, small plants operate nearly as efficiently as large ones. Fuel cell power plants can be built in a wide range of electrical output, ranging from watts to megawatts.

Efficiencies of present fuel cell plants are in the range of 40–55% based on the lower heating value (LHV) of the fuel. Hybrid fuel cell/reheat gas turbine cycles can offer efficiencies up to 70%, LHV. Fuel cells operate at a constant temperature, and the heat from the electrochemical reaction is available for cogeneration.

3. Dual-purpose plants

More than 25,000 MW of power are combined with desalination plants in cogeneration plants. Thermal energy from power plants is used to provide heat input to thermal desalination plants for MSF or multi-effect distillation (MED) processes. The electrical energy can be also used in desalination processes like RO and Vapor Compression Distillation (VC). Some examples of dual-purpose plants combining distillation technologies with gas or steam turbines, diesel generators and combined cycle unit are described in [5,7].

While electricity demand presents normally dramatic variations along the seasons, the demand for potable water is almost constant. As water can be stored, excess electricity can be shifted to water desalination through electrically driven technology of seawater RO and VC distillation and combined with the low pressure steam driven technology of MSF or MED, which presents an interesting benefit. One of the most relevant parameters in the design of these hybrid plants will be the power to water ratio (PWR). Hybrid desalting systems combining power, MSF plant and membrane seawater RO plant could offer significant advantages [8]:

- Common and smaller seawater intake and common treatment equipment for the product water for both plants.
- RO and MSF product are blended.
- The second stage RO process can be eliminated.
- Enlarge the membranes life.
- Allow power plant operating at full load (higher efficiency) more hours per year.
- RO feed seawater temperature could be increased using cooling water from the heat reject section of the MSF.
- The brine discharge from the RO plant is combined with the brine blowdown of the MSF plant to reduce its salinity.

4. Dual-purpose plants FC/MSF/RO

One of the waste streams in fuel cells systems is the waste heat contained in the flue gases stream. Depending on the type of fuel cell the heat flow has different qualities. Those fuel cell plants considered suitable for cogeneration can also be coupled with MSF or RO plants to produce distillated water. The proposal is studying a dual-purpose power/water hybrid plant where power is generated by a high temperature fuel cell system instead of using conventional power generation devices, and water is produced in a MSF plant and a RO system.

MCFC and SOFC are the most suitable technologies for cogeneration due to their significantly high operating temperatures, 650°C and 900°C respectively. The rest of fuel cells configurations operate at less than 250°C.

The block diagram of the FC plant coupled with two desalination technologies representing the main input and output flows is presented in Fig. 2. The fuel cell anode side is fed with natural gas or any other source of hydrogen. Fresh air and recycled CO_2 from the auxiliary boiler within the fuel cell system are fed in the fuel cell cathode side. The cooling system inside the fuel cell is a cycle, so there are not input or output flows related to it. The water generated during the operation of the fuel cell stack is reused in steam reforming reaction so this flow is shown as a recycle. The two other outputs of the FC system are AC electricity and exhaust gases stream. Power is directly fed to a RO unit to produce pure water and waste heat is used to produce low pressure steam in a Heat Recovery Steam Generator (HRSG).

Then, low pressure steam is introduced in a MSF desalination unit to produce additional desalted water. Water steam is condensed in the brine heater after MSF and reused in the HRSG unit. Both desalination units are fed with seawater stream which will become two different products: pure water and rejected brine.

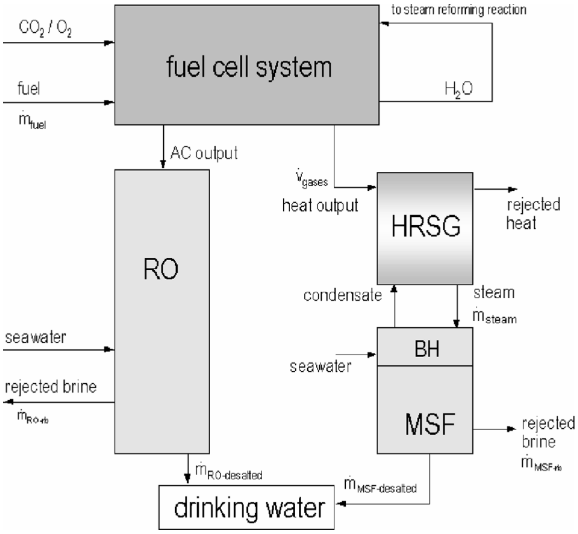

Fig. 2. Block diagram of a fuel cell coupled with a RO and a MSF units.

Table 1
Key performance data

RO unit:	
Specific electricity consumption, kWh/m^3	4
Recovery rate, %	35
Salt rejection, %	99
MSF desalination unit:	
GOR	10
Typical conversion, %	18
MCFC system:	
Electrical output, kW	245
Electrical efficiency, %	47
Temperature exhaust gases, °C	400
Volumetric flow exhaust gas, m^3/h	1500
Thermal performance, kW	180
Cp gases, kJ/m^3/°C	1.25
HRSG	
Heat exchanger efficiency, %	85
Temperature inlet water, °C	20
Temperature steam, °C	127
Pressure steam, bar 2.5 Enthalpy, kJ/kg	2751
Outlet temperature gases, °C	140

Key performance data are summarized in Table 1. These data include the efficiencies of the equipments, electrical consumption and properties of the different flows.

4.1. Reverse osmosis unit

The specific power consumption has been considered 4 kWh/m^3, a typical value when a Pelton turbine is selected as the energy recovery system (ERS).

4.2. Multi-stage flash desalination unit

The GOR is defined as the relation between mass of distillated water and mass of steam introduced in this unit. The quantity of steam fed into the unit will be fixed from the HRSG operation and it will directly depend on the waste heat released by the fuel cell system.

4.3. Molten carbonate fuel cell system

There are many different parameters which determine the internal performance of a fuel cell system but the required ones to define the operation within this installation are the electricity output, the electrical efficiency, the temperature of exhaust gases and its volumetric flow.

Data have been collected from MTU Friedrichshafen, MCFC manufacturing company, for a 245 kW MCFC (electrical useful performance) and extrapolated for a 500 kW MCFC. The electrical system efficiency is approximately 47%. Fuel consumption can be easily calculated from this efficiency and the electrical useful performance. The approximate temperature of exhaust gases is 400°C and the volumetric flow of this stream is 3000 m^3/h. These values are the inputs for HRSG unit. The electrical efficiency of the fuel cell block is 55% (before AC conversion). The maximum total efficiency when cooling down exhaust gases to 50°C is around 90% and the thermal performance around 360 kW. In our study the total efficiency and the thermal performance will be lower because exhaust gases are cooled down to a higher temperature (around 130°C). The emissions are classified as exhaust air in accordance with the Federal Inmission Control Act (BimSchG) in Germany. Exhaust air regulation are not required because SO_2 and NO_x traces are not found and CO concentration is lower than 9 ppm.

4.4. Solid oxide fuel cell system

The operation performance of this type of FC is very similar to the MCFC. There are not significant differences in electrical efficiencies and in exhaust gases flow stream. The gas temperature will be higher due to the higher operation temperature in SOFC, set as 600°C. The volumetric flow of exhaust gases is 3000 m^3/h.

4.5. *Heat recovery steam generator*

This unit is also a heat exchanger in which steam is produced, therefore the same statements above can be applied here. The temperature of the steam streams will be set according the requirements of the distillation system and the temperature of the exhaust gases can be set in the outlet.

5. Hybrid desalting systems: case studies

Different case studies are presented here for various concepts of dual plants run by fuel cells. Inlet seawater stream salinity is 36000 ppm TDS and 20°C. The concentration values of permeate in RO unit is 360 ppm of TDS and in MSF unit is even lower (<50 ppm). The concentration of the rejected flow will vary in every case depending on the conversion rate.

5.1. *MCFC 500 kW hybrid desalinating system*

The main values and relevant parameters when the fuel cell is fuelled by natural gas are shown in Table 2. The specific consumption of primary energy is 29.9 kJ of consumed natural gas per kg of desalted water. This value is similar to the specific consumption of reverse osmosis units with the best energy recovery systems, but in this case electricity is also produced.

The overall water desalination capacity of this system is 3074 m^3/day, but only 2.4% is produced in the MSF unit. It will represent high investment and maintenance costs for such a small percentage in the overall production. The global efficiency is 69%, when cold stream has lower exhausting temperatures this value could reach 90%.

Table 2
Values for MCFC hybrid plant fuelled by natural gas

RO unit:	
$m_{RO\text{-}desalted}$, m^3/day	3000
$m_{RO\text{-}rb}$, m^3/day	5571
MSF desalination unit:	
$m_{MSF\text{-}desalted}$, m^3/day	74
$m_{MSF\text{-}rb}$, m^3/day	334
MCFC system:	
m_{fuel}, kW	1064
m_{fuel}, kg/h	85
$V_{exhausted\ gases}$, m^3/h	3061
HRSG	
$Q_{exchanged}$, kW	235
m_{steam}, kg/h	308
Efficiency	69%

5.2. *SOFC 500 kW hybrid desalinating system*

The total production capacity of the system is higher when running SOFC due to the higher temperatures of the flue gases. The water generated by distillation does not reach the 5% of the overall production. The specific consumption (in terms of primary energy) is 29.3 kJ/kg. The overall efficiency of the system is 86%, justified by the higher working temperatures in SOFC (800–900°C) while the electrical efficiency is more or less the same for both types of fuel cells. It can be concluded that, from a technical point of view, SOFC system are more suitable for this application.

It can be concluded that thermal desalination systems will not be economically feasible because of the so limited amount of steam generated from the waste heat from the fuel cell.

6. Alternative fuels

There are many different possibilities to fuel the fuel cell systems. The easiest way is fueling with natural gas because it is constantly available, it has a high calorific

Table 3
Values for SOFC hybrid plant fuelled by natural gas

RO unit:	
$m_{\text{RO-desalted}}$, m^3/day	3000
$m_{\text{RO-rb}}$, m^3/day	5571
MSF desalination unit:	
$m_{\text{MSF-desalted}}$, m^3/day	131
$m_{\text{MSF-rb}}$, m^3/day	595
MCFC system:	
m_{fuel}, kW	1064
m_{fuel}, kg/h	85
$V_{\text{exhausted gases}}$, m^3/h	3061
HRSG	
$Q_{\text{exchanged}}$, kW	416
m_{steam}, kg/h	545
Efficiency	86%

value, its properties are commonly uniform, the pollutants present in the gas are well-known and the cleaning system required is not very complex. Other fuels tested in fuel cell systems are landfill gas, syngas from biomass gasifiers and bio-gas from anaerobic digesters in wastewater treatment plants.

6.1. Biogas from anaerobic digester

The precondition for the use of biogas in fuel cell is the elimination of detrimental trace gases, which are potentially harmful for fuel cells. In order to achieve it, a comprehensive biogas analysis in quality and quantity on a detailed level must be performed. The avoidance of detrimental trace gases in biogas through optimal composition of the feedstock and advanced controlling of the anaerobic digestion process to hinder the formation of trace gases while keeping a high CH_4 yield are essential.

The biggest problems addressed are trace gases such as H_2S, halogenated hydrocarbons and siloxanes. These trace gases significantly decrease the efficiency and durability of fuel cells. That means the utilization of biogas in fuel cells instead of usual gas engines to CHP generation cause a dramatically increase in required purity of the biogas fuel.

Biogas produced in anaerobic digesters consists of methane, carbon dioxide, and trace levels of other gases such as hydrogen, carbon monoxide, nitrogen, oxygen, and hydrogen sulfide. The relative percentage of these gases in biogas depends on the feed material and management of the process. Table 4 shows the typical range of values for the composition of biogas. In this paper, the methane content has been fixed as 75%, the biogas will have a calorific value of around 33750 kJ/kg. The operational results would be the same obtained with natural gas but the consumed flow of fuel in 500 kW FC has increased up to 113 kg/h (in the economic analysis, only volumetric flow and its cost are interesting).

6.2. Landfill gas

Landfill gas released into the air smells bad, contributes to local smog, and is an explosion hazard. Additionally, landfill gas is about 50% methane, a potent greenhouse gas that contributes to global climate change. However, this methane is also a reliable fuel source that can be fed into fuel cells. Table 5 shows the typical range of values for the composition of landfill gases.

The calculation of the calorific value has been performed considering 53% of methane

Table 4
Composition of biogas

Methane	54–80%
Carbon dioxide	25–50%
Nitrogen	0.5–3%
Hydrogen	1–10%
Carbon monoxide	0.1%
Oxygen	0.1%
Hydrogen sulfide	trace

Table 5
Composition of landfill gas

Methane	45–60%
Carbon dioxide	40–60%
Nitrogen	2–5%
Ammonia	0.1–10%
Oxygen	0.1–10%
Hydrogen	0–0.1 %

in the landfill gas. The calorific value of the gas will be 23850 kJ/kg. The consumed flow of fuel has increased to 160.5 kg/h for 500 kW fuel cell.

7. Dual-purpose plants FC/RO

Section 5 shows that the production of desalted water applying distillation technologies is less than 5% compared to membrane technology production capacity. Therefore, a new proposal disregarding MSF unit has been done (Fig. 3).

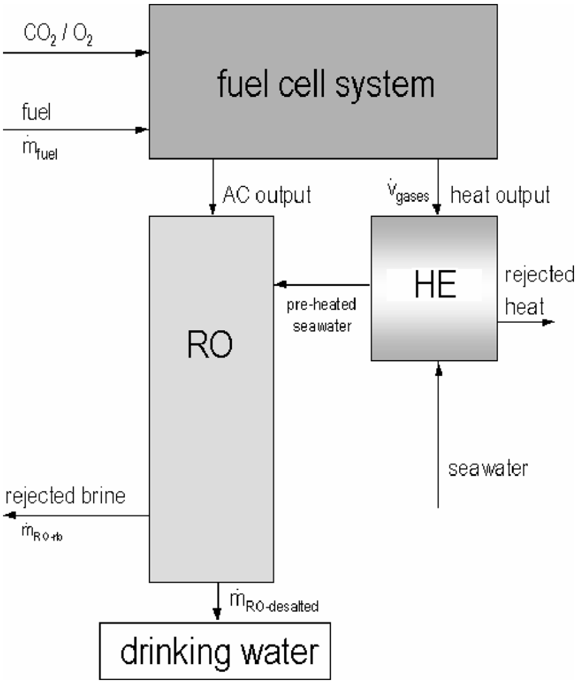

Fig. 3. Block diagram of the preheating concept.

This new concept saves all the costs related to MSF technology and offers a new opportunity to use the waste heat. In RO units, temperature has a significant effect on osmotic pressure and permeates flow. The heat released in the fuel cell is used for preheating the seawater to be desalted in the RO unit 2 or 3°C. Preheating the seawater prior to the reverse osmosis process allows a reduction in the water pressure required to keep the production constant. It is not recommended to preheat the seawater temperature up to 40°C because of problems of fouling and membrane deterioration.

As Al-Bahria et al. [9] state, the required pressure preheating seawater to 35°C decrease from 58.5 bar down to 51.5 bar. Therefore, energy demand for RO unit operation would also decrease. The results of the energy balances for this proposal using different fuel cell technologies are shown in the following. The fuel is natural gas.

7.1. MCFC dual-purpose plant

The new desalting capacity of the RO unit with an electrical input of 500 kW would be 3103 m^3/day The available heat from the flue gases is 334 kW when cooling down the exhaust gases down to 30°C. This power could heat 2.23°C the mass of water to desalt, decreasing the high pressure pump consumption to 3,866 kWh/m^3 desalted water. Compared to the former configuration, the plant is producing an extra 2% of the overall production using only membrane technology. The increase related to the RO water desalination is around 4.7%. The efficiency has increased to 78%.

7.2. SOFC 500 kW dual-purpose plant

The temperature of the flue gases, 600°C, is high enough to heat up 3158 m^3 / day to 23.36°C. This temperature produces a specific

Table 6
Data calculation for MCFC dual-plant

RO unit:	
$m_{\text{RO-desalted}}$, m^3/day	3103
$m_{\text{RO-rb}}$, m^3/day	5763
MCFC system:	
m_{fuel}, kW	1064
m_{fuel}, kg/h	85
He	
$Q_{\text{exchanged}}$, kW	334
$T_{\text{out-gases}}$, °C	30
Efficiency	78%

consumption of the reverse osmosis plant of 3.79 kWh/m^3. Taking into account only the reverse osmosis unit the present desalination capacity of the unit is 5.5% higher. The energy use reaches the 95%.

8. Costs analysis

After showing the interest of the combined production of water and power driven by high temperature fuel cells, the economical feasibility of this kind of plants is analyzed. The different proposed concepts are summarized and compared on a benefits basis. The costs related to every unit are the investment costs and the costs of operation and maintenance. The present prices of fuel cells are very high because they still are at their development stage. In order to have a more realistic economic analysis of the systems the future target price has been also considered.

Table 7
Data calculation for SOFC dual-plant

RO unit:	
$m_{\text{RO-desalted}}$, m^3/day	3158
$m_{\text{RO-rb}}$, m^3/day	5866
MCFC system:	
m_{fuel}, kW	1064
m_{fuel}, kg/h	85
He	
$Q_{\text{exchanged}}$, kW	513
$T_{\text{out-gases}}$, °C	32.5
Efficiency	95%

8.1. Investment costs

Table 8 shows the investment costs of the fuel cells installed in the studied systems for the present situation and the target one. The future scenario assumes the continuous production of fuel cells. The investment cost of the desalination systems depend on the amount of processed water, the more production the less relative cost. The investment costs of these units in the systems are also shown in Table 8.

8.2. Operation & Maintenance costs

O & M costs for the RO unit has been calculated as 407 €/day. The costs related to heat exchangers and the heat recovery steam generation have not been considered because they are significantly lower than those of the desalination units. It has been not possible to find a reliable estimation of operational costs for fuel cells.

8.3. Amortization costs

The capital costs are amortized along the life-time of the equipments. It has been considered a useful life for the fuel cell of 5 years in the future scenario and a 3 years at present (the limiting factor is the life of the stack).

Table 8
Investment costs of the different units in the system

UNIT	Present investment cost
MCFC 500 kW	1,000,000 €
SOFC 500 kW	9,000,000 €
RO Unit – 3000 m^3/day	3,780,150 €
Heat Exchanger	626 €
UNIT	**Future investment cost**
MCFC 500 kW	500,000 €
SOFC 500 kW	500,000 €

Table 9
Economical parameters

Interest rate, %	3
Life-time of the system, years	20
Water price, €/m^3	0.68
Natural gas price, €/kWh	0.023
Electricity price, €/kWh	0.082

The other equipments life-time has been considered 20 years.

8.4. Annual incomes

The annual incomes include the water and energy savings. Water savings are calculated on the average price of water basis. The electricity savings includes the electrical energy consumed in the plant and generated in the system.

9. Economical analysis of dual plants

The economical analysis of the combined plant disregarding the MSF plant will be interesting. Tables from 9 to 11 show the economical parameters and data summary for the different fuel cells dual plants making use of the waste heat.

Table 10
Economic analysis summary MCFC dual plant

Fuel costs	214,340 €/year
O & M costs	153,539 €/year
TOTAL COSTS	367,879 €/year
Water savings	770,292 €/year
Electricity savings	359,160 €/year
INCOMES	1,129,452 €/year
BENEFITS	761,573 €/year
PRESENT SCENARIO	
NPV	819,072 €
RP	18 years
FUTURE SCENARIO	
NPV	5,419,072 €
RP	9 years

Table 11
Economic analysis summary SOFC dual plant

Fuel costs	214,340 €/year
O & M costs	156,271 €/year
TOTAL COSTS	370,612 €/year
Water savings	784,001 €/year
Electricity savings	359,160 €/year
INCOMES	1,143,161 €/year
BENEFITS	772,549 €/year
PRESENT SCENARIO	
Npv	−51,887,228 €
RP	– years
FUTURE SCENARIO	
Npv	5,512,771 €
RP	9 years

Under present conditions, we could argue that the project is not feasible because the RP is too high. This value is reduced in almost a 50% short-period future scenario (less than 20 years), showing an interesting perspective.

10. Alternative fuels costs

The use of fuels from renewable sources is a very promising alternative when running fuel cells. The influence in the economic analysis will be an increase in the investment costs related to the pretreatment unit for the biogas/landfill gas and its operation and maintenance costs.

The purpose of this section will be the analysis of the economical feasibility of systems with pretreatment units. Due to the high diversity of pretreatment systems in the market and the big differences of the gas composition depending on the characteristics of the landfill or the anaerobic treatment, the study of specific equipment is not representative. Therefore, the economical study will be shown considering the costs related to the pretreatment unit as a percentage of the total investment. The costs boundaries to avoid an economical impact by installing these pretreatment units will be set.

Figure 4 presents the maximum costs per year that can be invested in the pretreatment unit to obtain the same benefits calculated for natural gas as fuel. It has been calculated for different prices of the landfill gas. The lowest the price, the highest the percentage of the total cost saved to establish the appropriate treatment plant. Whit free-alternative fuels, a saving between 13 and 24% of the total costs can be conducted to invest in cleaning systems.

11. Conclusions

After performing technical analysis of different types of desalination schemes driven by fuel cells, the most profitable one is clearly the RO unit with preheating. The efficiencies of these systems are 78% and 95% for MCFC and SOFC respectively and the specific consumption of primary energy is around 29 kJ/kg for both fuel cells.

The economical analysis shows that the project is not profitable for SOFC under present conditions due to their extremely high investment costs and the MCFC system presents a recovery period of 18 years. Therefore, neither SOFC nor MCFC configurations are interesting investments.

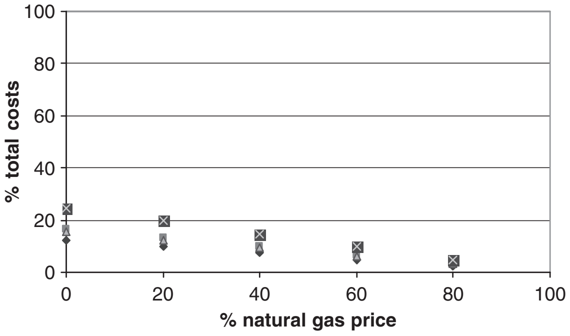

Fig. 4. Possible investments in pretreatment systems using alternative fuels.

The recovery period is reduced to 9 years when considering target investment costs and net present values (20 years) are quite similar for both FC. This means that those integrated systems are really promising in a near future, although some estimations point that this technology will not be available before 2008.

When fueling the system with alternative gases, the investment and operational costs of the pretreatment unit should be set before making any choice. Another relevant factor will be the gas production capacity of the landfill or wastewater treatment. It must ensure the energy demand of the fuel cell system. If benefits are similar (natural gas vs. biogas), environmental advantages of the alternative fuels must be considered.

12. Acknowledgements

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13. Nomenclature

RO: reverse osmosis
VC: vapor compression
MSF: multi-stage flash
MED: multi-effect distillation
FC: fuel cell
MCFC: molten carbonate fuel cell
SOFC: olid oxide fuel cell
HRSG: heat recovery steam generator
HE: heat exchanger
LHV: lower heating value
TDS: total dissolved solids
NPV: net present value

RP: recovery period m: mass flow
V: volumetric flow
Q: heat flow exchanged

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