FERRET

A FLEXIBLE NATURAL GAS MEMBRANE REFORMER FOR M-CHP APPLICATIONS

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PP	Restricted to other programme participants (including the Commission Services)	
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Content

1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

This deliverable concerns the economic analysis of Ferret unit in case of mass production.
First, fuel processor costs are examined (membrane reactor, catalyst, membrane, methanator), showing the impact of methanation reactor and of different typology of membrane on its cost. Besides, balance of plant and fuel cell stack costs are discussed. Finally, cost of each part discussed in the firsts paragraphs, are merged to give a cost overview of Ferret unit, describing the impact of each item on the total system cost.

2 INTRODUCTION

This deliverable deals with economic evaluation of Ferret unit.
As a general consideration, this analysis is not focalized on the costs incurred within the project for prototype development and manufacturing, because a great effort in terms of money and time was provided in order to define, develop and manufacture the prototype. Moreover, the prototype is equipped with several and redundant instrumentation for measuring and managing the system, in order to investigate several parameters and understand the unit behavior. The prototype is also equipped with instrumentation normally used in laboratory and field test experiments (like for example a PLC instead of a circuit board in case of mass production). For this reason, if the analysis of costs take into account the one occurred within the project for prototype manufacturing, this could give an image faraway from the commercial objective.
Based on previous consideration, the aim of the deliverable is to present and analyze costs of Ferret unit in case of market entry with a production of 1000 units per year, taking into account cost reduction due to economy of scale (procurement and manufacture of hundreds devices and items).
All the data are collected among the partners whom supply the specific component.

3 FUEL PROCESSOR

This paragraph deals with fuel processor costs. The fuel processor (FP) is the membrane reactor (MR) plus catalyst and membrane; also methanator is considered as part of the FP and will be discussed. The methanator reactor was introduced within this project in order to meet the needs of fuel cell stack in case of limited membrane leakages, causing contamination of pure hydrogen permeate. In this paragraph, comparison between the case of FP with or without methanator is presented.

The MR is intended as the metal shell with its flanges, pipes and tubes, the costs estimated by the manufacturer is around 4000 € in case of production of 1000 units per year. This estimation is the result of material cost for the reactor with high thickness, and labor cost like welding and manufacturing of parts (flanges with holes, head with pipes, pipes). Considering 5 kW_e as power output of Ferret unit, specific cost of the reactor's shell is 800 €/kW_e.

Membranes cost have been fully investigated in D3.9. That document describes cost of four typology of membrane for semi-industrial scale production. **Error! Reference source not found.** summarizes costs for each typology of membrane. Table 1 summarizes also the permeance, considering the same operating conditions (temperature and pressure), and the ratio of this parameter to Ferret membrane permeance. This allows to calculate the total area needed, using different type of membrane, in order to achieve the target of hydrogen produced by Ferret unit. As reference is used the total membranes area used in the FP of Ferret unit, which is around 0.18 m^2, as declared in D5.3.
Finally, the total cost of membranes are showed, considering the specific cost and the calculated membrane area needed.

Table 1 Membranes cost

	Ceramic supported Pd-Ag membrane (CSM)	Metallic supported Pd-Ag membrane (MSM)	Ceramic supported Pd-Ag-Au membrane (CSM-Au)	Ceramic supported Double-skinned membrane (CSM-DS)
Cost for 1 m^2 membrane	6800	10200	7900	5700
H2 permeance (mol m^{-2} s^{-1} $Pa^{-0.5}$) at 400 °C	3.00E-03	7.60E-04	2.5E-03	3.5E-03
Ea (kJ/mol)	10	5.8	16	5.1
Permeance at 600 °C	4.5E-03	9.6E-04	4.9E-03	4.3E-03
Ratio permeance to reference	1.00	0.21	1.07	0.95
Membrane area needed for the system (m^2)	0.18	0.84	0.17	0.19
Cost of the membranes for the system (€)	1224	8607	1324	1075

Concerning the mix between catalyst and filler, used to give proper characteristic to fluidize bed in order to convert the methane, an estimation of costs is 370 €/l for catalyst and 25 €/l for filler. Catalyst cost also assumes some reduction in the Rh content of the catalyst from further catalyst optimization.
Going through D5.3, it is possible to find out that catalyst amount is around 2.6 l, while the amount of filler used is 1.8 l.
Merging previous data, catalyst total cost is 962 € and filler total cost is 45 €. Total cost of the reactant material which fill the reactor is around 1007 € for 1000 units produced per year. This means a specific cost of catalyst + filler of 201.4 €/kW_e, for 5 kW_e Ferret unit.

Methanator cost estimation is around 500 € for mass production. Compared to reactor used for the prototype developed within the project, the cost is decreased by around 50 %. This cost reduction is estimated to be linked mainly to labour cost of manufacturing. Indeed, significant number of units produced per year give the possibility to plan the use of a welding robot instead of a welder, increasing the productivity per hour. Machining purposes increase also their productivity, decreasing the costs. On the other side, raw materials do not decrease cost consistently as the catalyst for methanation reaction. In case of mass production, methanator will have a reduction in costs due to high volume of production but not as MR, because MR catalyst has been developed within the project and then, as pointed out, some optimization on the noble metal amount can be done. While the catalyst for methanation reaction is a commercial catalyst supplied by Johnson Matthey.
In the following analysis two different cases (with and without methanator) are proposed, depending on permeate purity obtained through membranes.

The following tables summarize total and specific costs of FP with methanator. It is possible to see the low impact of the reactor for methanation (around 7% or even 3.5% in case of MSM) compared to the other reactor. In addition, it is evident that the membrane + catalyst do not affect excessively the total cost of FP in case of ceramic membrane. While the cost of metallic membrane seems to become significant.

Table 2 FP cost with methanator and CSM

	€	€/kW$_e$	-
MR reactor	4000	800	59.4%
Catalyst + filler	1007	201	15.0%
Membrane CSM-DS	1224	245	18.2%
Methanator	500	100	7.4%
Fuel processor Tot.	6731	1346	100.0%

Table 3 FP cost with methanator and MSM

	€	€/kW$_e$	-
MR reactor	4000	800	28.3%
Catalyst + filler	1007	201	7.1%
Membrane CSM-DS	8607	1721	61.0%
Methanator	500	100	3.5%
Fuel processor Tot.	14114	2823	100.0%

Table 4 FP cost with methanator and CSM-Au

	€	€/kW$_e$	-
MR reactor	4000	800	58.6%
Catalyst + filler	1007	201	14.7%
Membrane CSM-DS	1324	265	19.4%
Methanator	500	100	7.3%
Fuel processor Tot.	6831	1366	100.0%

Table 5 FP cost with methanator and CSM-DS

	€	€/kW$_e$	-
MR reactor	4000	800	60.8%
Catalyst + filler	1007	201	15.3%
Membrane CSM-DS	1075	215	16.3%
Methanator	500	100	7.6%
Fuel processor Tot.	6582	1316	100.0%

Through Table 6 to Table 9, summarizing total and specific costs of FP without methanator, is possible to appreciate the real FP cost, and how the neglected reactor marginally affects the final cost.

Table 6 FP cost without methanator and CSM

	€	€/kW$_e$	-
MR reactor	4000	800	64.2%
Catalyst + filler	1007	201	16.2%
Membrane CSM-DS	1224	245	19.6%
Methanator	-	-	-
Fuel processor Tot.	6231	1246	100.0%

Table 7 FP cost without methanator and MSM

	€	€/kW$_e$	-
MR reactor	4000	800	29.4%
Catalyst + filler	1007	201	7.4%
Membrane CSM-DS	8607	1721	63.2%
Methanator	-	-	-
Fuel processor Tot.	13614	2723	100.0%

Table 8 FP cost without methanator and CSM-Au

	€	€/kW$_e$	-
MR reactor	4000	800	64.2%
Catalyst + filler	1007	201	16.2%
Membrane CSM-DS	1324	265	21.2%
Methanator	-	-	-
Fuel processor Tot.	6331	1266	101.6%

Table 9 FP cost without methanator and CSM-DS

	€	€/kW$_e$	-
MR reactor	4000	800	29.4%
Catalyst + filler	1007	201	7.4%
Membrane CSM-DS	1075	215	7.9%
Methanator	-	-	-
Fuel processor Tot.	6082	1216	44.7%

4 BoP AND STACK

Balance of plant (BoP) is composed of several sensors and components. Within the project, the prototype was equipped with redundant sensors or controller and with some oversized components (like heat exchangers), in order to achieve successful completion of projects goals. For this reason, it is misleading analyze the costs of prototype BoP as developed within the project, because it result in an overestimated value. For this purpose, only the estimation of costs concerning future Ferret system, with components of the correct size and without lots of redundancies, is taken into account.
Table 10 summarizes the actual BoP.

Table 10 BoP components assembled into Ferret prototype

Desulfurizer	-
Heat exchangers	permeate, retentate, water/steam, air
Manifolds	hydrogen, offgas discharge
Pumps	sweep, process, stack coolant, hydrogen, user circuit
Gases meter	natural gas, air, hydrogen
Flowmeters	nitrogen, air, natural gas, hydrogen
Air blower	fuel cell cathode
DC/AC inverter	interface grid-system
Humidifiers	-
Air filter	process and cathode air filter
Water trap	-
Control boxes	thermocouple, PLC, board PC, Netbiter
Pressure sensors	-
Pressure regulators	nitrogen, air, natural gas, hydrogen
Temperature sensors	thermocouples
Other sensors	oxygen, water level
Measurement power box	current and voltage sensor
Valves	two ways, three ways, pneumatic, solenoids, electromechanics
Check valves	-
Connections and pipes	stainless steel, copper, manual valves
Electrical components	cables, connectors
System production/assembly	electrical and mechanical components assembly + debug testing

Most of the components and sensors assembled into the prototype will be the same for final system to be produced for mass production. However, redundant sensors will be excluded and oversized components will be optimized decreasing cost. From this consideration, in case of mass production, has been estimated a total cost of 13000 € and a specific cost of 2600 €/kW_e for BoP.

Considering the fuel cell stack used for the purpose of the project, it is a commercial stack, not developed within the consortium. This is a component designed for automotive applications, operating with pure hydrogen.
The requirement to use an automotive FC stack, arises from the wide market this kind of devices have, compared to that for stationary application working with syngas (tolerating 10-30 ppm of CO). In addition, components for automotive sector usually reach low costs and important mass production in a very short time. This is the strength of this kind of fuel cells. Indeed, from a report of the US government of last year[1], it is possible to understand that following the reduction in platinum content of fuel cell catalysts (five times less) and the development of durable membrane electrode assemblies, the modeled cost is 53 $/$kW_e$ (50 €/kW_e) when produced at 500,000 units per year, and 59 $/$kW_e$ (55 €/kW_e) when produced at 100,000 units per year.
The FC stack used within the project has 75 cells, with a nominal power of 6 kW_e. Total cost of the stack modelled by US government is 330 €, using the suggested value of 55 €/kW_e.
Table 11 summarizes total and specific cost of BoP and FC stack.

[1] https://energy.gov/eere/fuelcells/fuel-cell-technologies-office-accomplishments-and-progress

Table 11 BoP + FC stack cost

BoP	13000 €	2600 €/kW$_e$
Fuel Cell	330 €	66 €/kW$_e$
Tot.	13330 €	2666 €/kW$_e$

From this analysis is interesting to understand how fuel cell stacks cost decreased during last years, turning into accessible components for this kind of systems.

5 WHOLE SYSTEM

After discussing main parts of the Ferret system cost, in this paragraph the total cost of Ferret unit is considered.
Total cost of each configuration is summarized in following tables (from Table 12 to Table 19)

Table 12 Ferret unit cost with methanator and CSM

	€	**€/kW$_e$**	**-**
MR reactor	4000	800	19.9%
Catalyst + filler	1007	201	5.0%
Membrane CSM-DS	1224	245	6.1%
Methanator	500	100	2.5%
BoP	13000	2600	64.8%
Fuel Cell	330	66	1.6%
Fuel processor Tot.	20061	4012	100.0%

Table 13 Ferret unit cost with methanator and MSM

	€	**€/kW$_e$**	**-**
MR reactor	4000	800	14.6%
Catalyst + filler	1007	201	3.7%
Membrane CSM-DS	8607	1721	31.4%
Methanator	500	100	1.8%
BoP	13000	2600	47.4%
Fuel Cell	330	66	1.2%
Fuel processor Tot.	27444	5489	100.0%

Table 14 Ferret unit cost with methanator and CSM-Au

	€	**€/kW$_e$**	**-**
MR reactor	4000	800	19.9%
Catalyst + filler	1007	201	5.0%
Membrane CSM-DS	1324	265	6.6%
Methanator	500	100	2.5%
BoP	13000	2600	64.8%
Fuel Cell	330	66	1.6%
Fuel processor Tot.	20161	4032	100.5%

Table 15 Ferret unit cost with methanator and CSM-DS

	€	€/kW$_e$	-
MR reactor	4000	800	14.6%
Catalyst + filler	1007	201	3.7%
Membrane CSM-DS	1075	215	3.9%
Methanator	500	100	1.8%
BoP	13000	2600	47.4%
Fuel Cell	330	66	1.2%
Fuel processor Tot.	19912	3982	72.6%

Table 16 Ferret unit cost with CSM and without methanator

	€	€/kW$_e$	-
MR reactor	4000	800	20.4%
Catalyst + filler	1007	201	5.1%
Membrane CSM-DS	1224	245	6.3%
Methanator	-	-	-
BoP	13000	2600	66.5%
Fuel Cell	330	66	1.7%
Fuel processor Tot.	19561	3912	100.0%

Table 17 Ferret unit cost with MSM and without methanator

	€	€/kW$_e$	-
MR reactor	4000	800	14.8%
Catalyst + filler	1007	201	3.7%
Membrane CSM-DS	8607	1721	31.9%
Methanator	-	-	-
BoP	13000	2600	48.2%
Fuel Cell	330	66	1.2%
Fuel processor Tot.	26944	5389	100.0%

Table 18 Ferret unit cost with CSM-Au and without methanator

	€	€/kW$_e$	-
MR reactor	4000	800	20.4%
Catalyst + filler	1007	201	5.1%
Membrane CSM-DS	1324	265	6.8%
Methanator	-	-	-
BoP	13000	2600	66.5%
Fuel Cell	330	66	1.7%
Fuel processor Tot.	19661	3932	100.5%

Table 19 Ferret unit cost with CSM-DS and without methanator

	€	€/kW$_e$	-
MR reactor	4000	800	14.8%
Catalyst + filler	1007	201	3.7%
Membrane CSM-DS	1075	215	4.0%
Methanator	-	-	-
BoP	13000	2600	48.2%
Fuel Cell	330	66	1.2%
Fuel processor Tot.	19412	3882	72.0%

The weight of each item on the final cost is showed in following diagrams (**Error! Reference source not found.** and Figure 2)

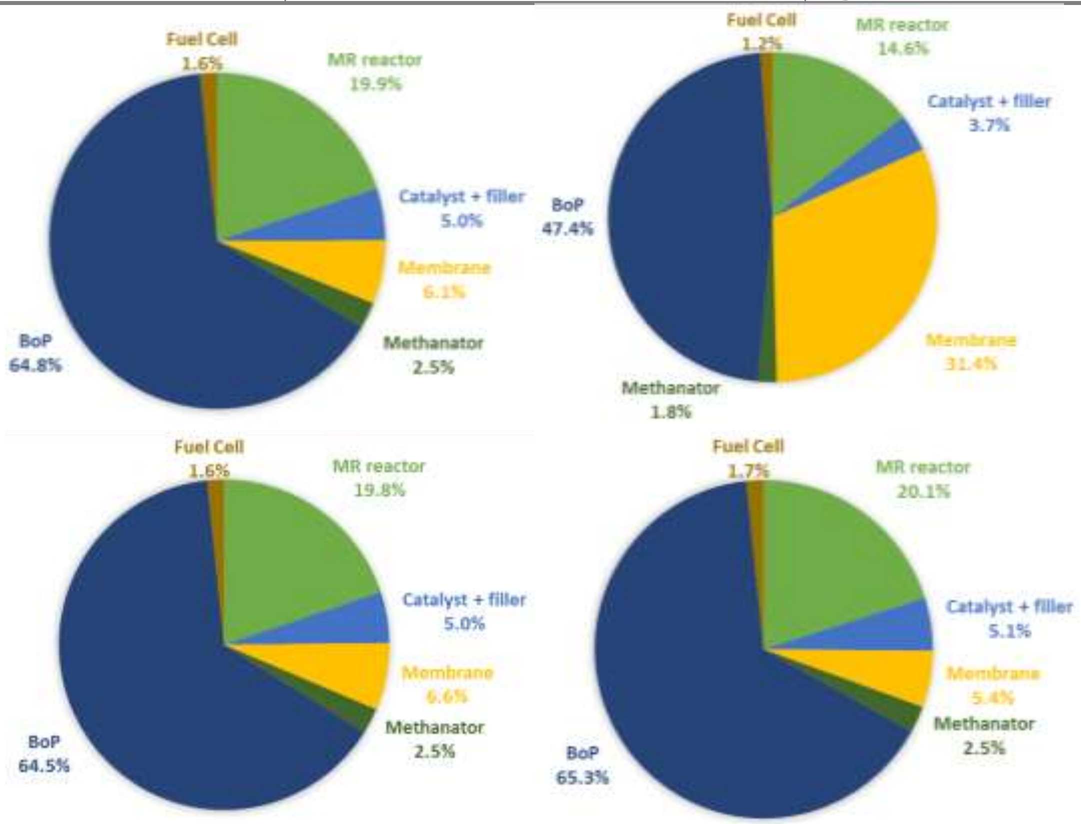

Figure 2. Ferret unit cost with methanator

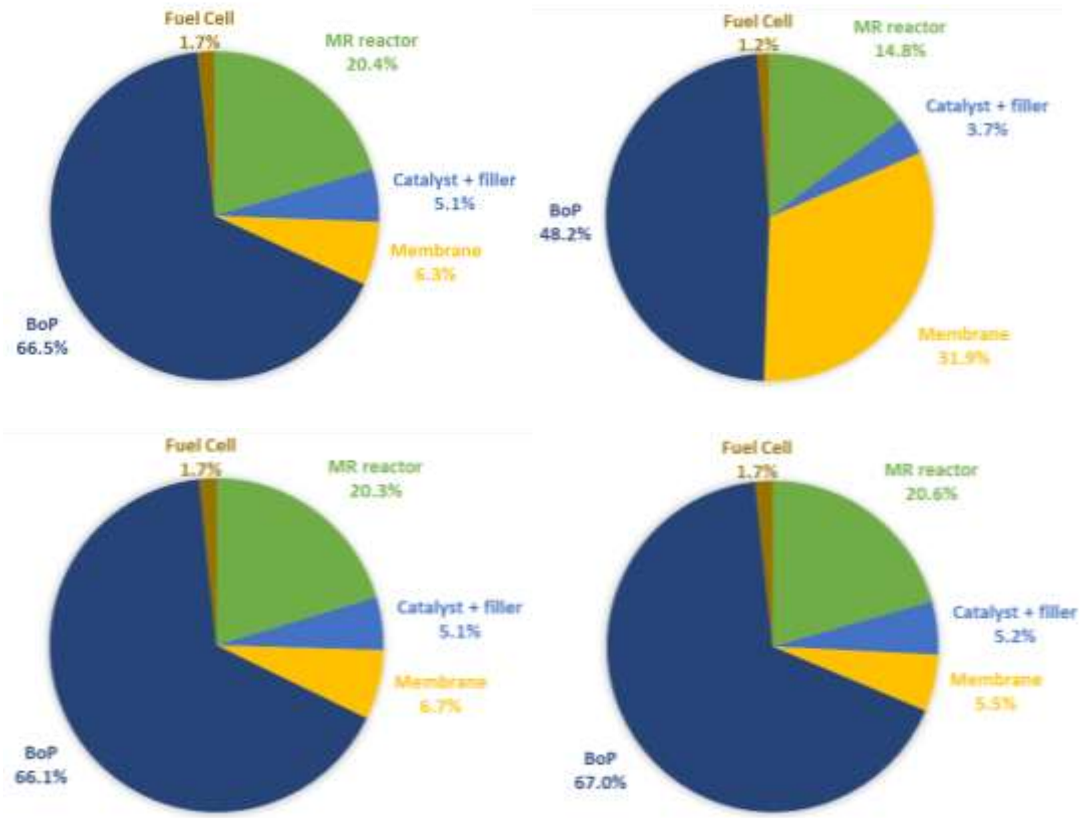

Figure 1. Ferret unit cost without methanator

It is possible to appreciate the weightless impact of the methanator reactor, which is around 2.5% on the final cost of the system.
From the previous tables and diagram, it is also possible to learn how BoP cost affect considerably the total Ferret unit cost, as well the membrane reactor.
Following the investigation of the US government on fuel cell, it seems that, during last months and surely during next years, FC stacks get extremely cheap price. Last years, FC cost had a high impact on the total cost of CHP system based on this kind of technology, while in the immediate future appear to not affect the CHP total cost.
Comparing also the impact of metallic supported membrane on the final unit cost it is possible to see that it does not affects significantly the total cost.
From this analysis, BoP is the main cost of the system due to its several components and sensors. This is consistent with the system as a whole due to the several components collected into this grouping (**Error! Reference source not found.**).

6 CONCLUSION

Ferret unit cost in case of mass production have been analysed.
First, fuel processor cost has been considered. The FP was split into membrane reactor, catalyst and membrane. It was showed also the case with and without methanator and an overview of different type of membranes was provided. From this analysis, it was easy to appreciate how the impact of methanation reactor is not so significant on FP total cost. Besides, membranes and catalyst do not have particular impact on FP total cost. Finally, metallic supported Pd-Ag membranes affects total cost more than ceramic supported membranes.
Considering the fuel cell stack, results of US government analysis are very interesting for CHP systems based on this kind of technology. They show how is significant the cost reduction of this kind of devices.
Compared to the cost target of 2300 €/kWe for whole system, pointed out in Task 6.6, Ferret unit cost estimation is still quite high in case of mass production in few years. It costs around 50% of the target cost. However, it is consistent with the milestone fixed by European Hydrogen and Fuel Cell Technology Platform, which was having 80.000 1-10kW FC systems for residential CHP installed, at a cost of under 5000 - 6.000 €/kW_e by 2015.
Future works should make a great effort in terms of Ferret unit cost, optimizing BoP components, and membrane and catalyst production procedure, making the system more competitive against other CHP technologies. Moreover, an aspect that would require further attention in the coming phases of system development are servicing and maintenance protocols and costs involved. In particular due to service required in the membrane reactor, replacement rate within the lifetime of the system, and level of recyclability (may also refurbishing) of the reactor.
Finally, to conclude, it is important to take into account that, when the market of this kind of system take hold worldwide, and more units will be requested from the international market, with thousands of Ferret units produced, costs will fall down considerably, following the same curve of fuel cell stacks costs.