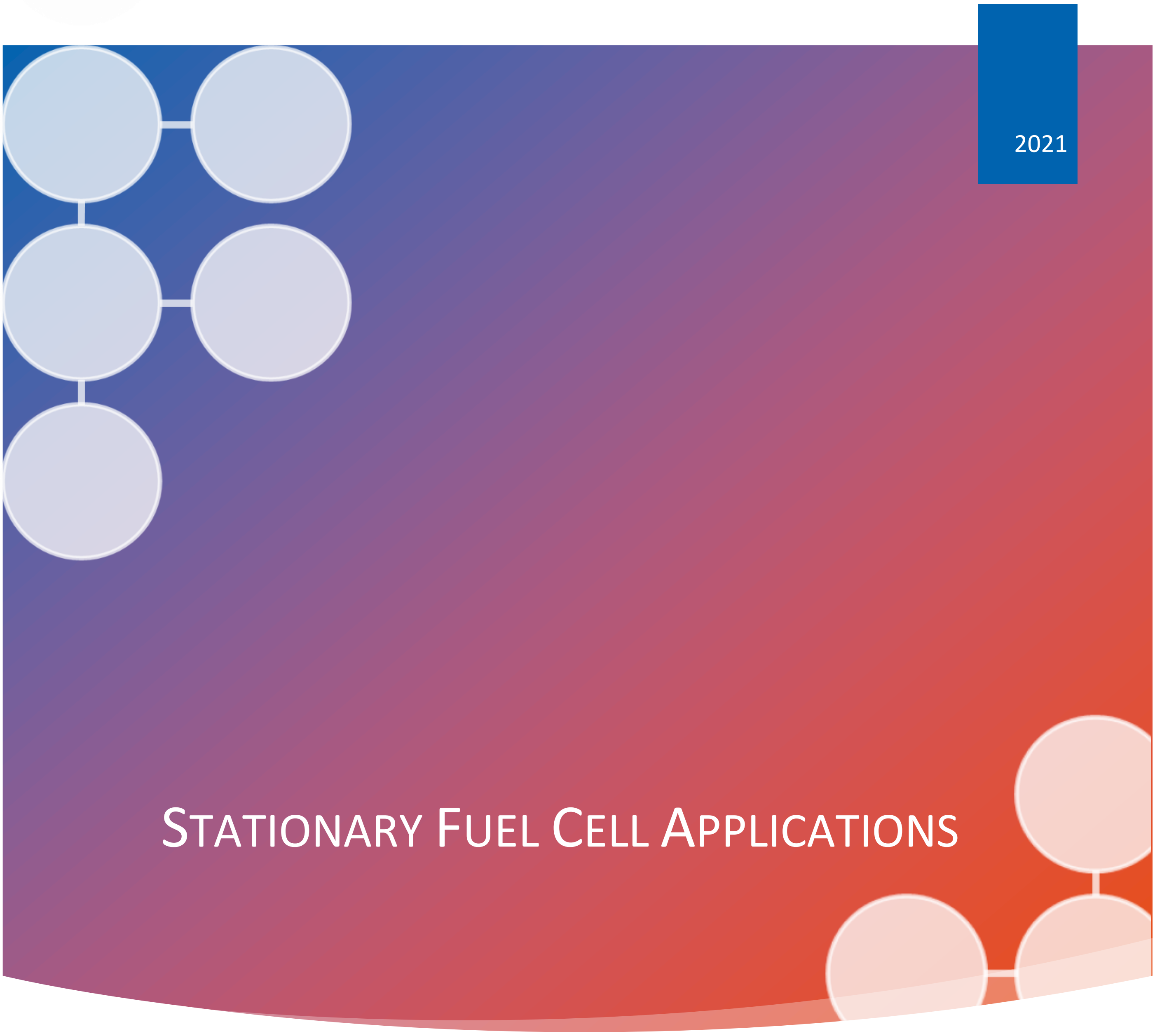

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STATIONARY FUEL CELL APPLICATIONS

CURRENT AND FUTURE TECHNOLOGIES - COSTS, PERFORMANCES, AND POTENTIAL

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Advanced Fuel Cells

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STATIONARY FUEL CELL APPLICATIONS: CURRENT AND FUTURE TECHNOLOGIES - COSTS, PERFORMANCES, AND POTENTIAL

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Abstract – Stationary power and cogeneration systems will surely need research and innovative actions towards a more energy efficient and more resilient energy network. Fuel cell systems can become key technologies and system enablers, since their performance is higher than conventional systems. Efficiency, stack durability, capital expenditure, maintenance activities and potential failures need to be investigated. The present report aims to analyze the worldwide performance of these technologies, with a particular focus on PEM and SOFC, for different sizes and range of applications, from 0.5 kW up to several Megawatt. The state-of-the art is presented, in terms of costs and performance, and forecasts up to 2030 are reported, calling for a specific investment cost drop between 1000-3000 €/kW of installed capacity.

1. INTRODUCTION

Among the several options the scientific community is recognized as key-elements to address climate change and fossil fuel-dependence. Fuel cell technologies have been identified as the best options to decarbonize the stationary power production sectors, including primary power, backup power and combined-heat-and-power configurations (CHP) [1].

Fuel cell technologies are capable of providing very high efficiency, minimum pollution, and high reliability.

It is indeed important to track and investigate the performance of such systems, providing some interesting data on the state-of-art of the performance, as well as on some forecasts for the upcoming years. In deeper detail, the present report will list a potential breakdown of the current costs for PEM/SOFC (Polymer Electrolyte Membrane/ Solid Oxide Fuel Cell) production for building applications over a range of production scales and representative specifications, as well as broken down by component/material. Inherent to the technology performance, a coincide estimation on FC system durability, efficiency, production, maintenance and capital costs will be presented.

Finally, some potentials for cost reductions and durability improvements, as well as strategies of reducing costs and improving performance for a number of the components of FC stacks, will be presented.

The documentation for conducting the present study is based on the high-specialized scientific literature, academic articles in journals, technical papers and reports related to fuel cell application topics, and scientific databases.

2. BREAKDOWN OF THE CURRENT COSTS

The main sectors where stationary fuel cells have been employed are micro-CHP and large stationary applications. With particular attention to the building sector, fuel cells resulted to be very suitable for micro-cogeneration and CHP because these energy systems inherently produce both electricity and heat from only one source of fuel. That could be innovative and more efficient, even if more expensive fuels, such as hydrogen, are used. These systems can also operate by adopting traditional fuels, such as biogas, methane and natural gases, after being properly reformed.

The design parameters for the stationary fuel cell system differ according to fuel cell technology (PEM, AFC, PAFC, MCFC, SOFC), as well as to the fuel typology and supply.

For building applications and micro-cogeneration, PEM systems are the most common fuel cell type used and installed, being more mature than other technologies, and guaranteeing high efficiency, covering the peak energy demand during the day, and covering also the energy needs at night. On the one hand, PEM fuel cell operations can benefit from its low temperature requirement, a solid membrane electrolyte installation, which strongly reduces maintenance cost, degradation phenomena and corrosion, and a quick start-up. On the other hand, low temperatures lead to the adoption of expensive catalyst, since the system is thus very sensitive to the presence of carbon impurities, most common if these systems run with reformed fuels.

As a raising technology, SOFC systems are gaining more credit. A SOFC can operate at higher temperatures, reducing the catalyst strict requirements, allowing a greater tolerance to carbon monoxide, and thus simplifying the system in terms of needed purification system at the reformer level. This fuel flexibility represents a key enabler towards the hydrogen economy transition, allowing also greater efficiencies. SOFC have also been investigated to operate in a reversible-mode (SOE), capable of producing hydrogen when it is needed. Otherwise, high temperatures require longer start-up time, and a limited number of shut-down procedures, since thermal stress on the stack components can lead to corrosion and breakdowns of the components of the stack itself.

It is noticeable how these systems present a potential solution for cogeneration applications for buildings and districts. Currently, the units, which have been installed in buildings, provided the energy needs of a small district system, composed of collective houses or apartments. In order to decrease the costs and to produce systems with lower power capacities, governments and states promoted financial programs to sustain the transition of these technologies, from research and development, towards early-market adoption. Among the several worldwide actions, Japan and Europe are taking lead in fuel cell-based CHP fundings and applications. Japan is the main leader in CHP installations, with the ENEFARM program in which more than 314,000 units have been installed. They have been able to decrease the price per sale to 7,000 US$/unit for PEM, and 8,800 US$/unit for SOFC [2,3]. Europe has installed more than 4,100 of CHP units [4], thanks to three main actions [5]: Callux, PACE and ene.field. Sole in the ene.field program, 603 PEM micro-CHP units have been installed, and 403 SOFC.

Within these European Projects, Nielson et al. [6] investigated the reliability, performance and availability of 67 units, by means of a failure analysis, reporting interesting results, as shown in Figure 1.

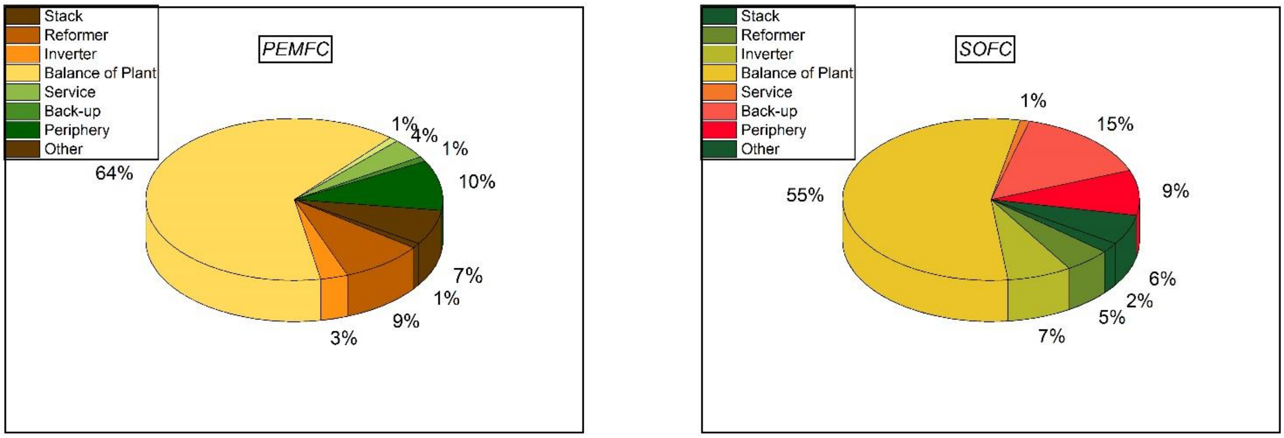

Figure 1: Fuel Cell Failures, retrieved from [4–6]

The analysis showed how “45% experienced no failures in the first year of operation and an availability of 100%”, followed by 19% with 1 failure, with an availability of 98.2%, and finally 24% with 2 failures (98.3% of availability), and 13% with more than 3 failures occurred, being however available for 86.9% of the overall operation. The authors have marked how “90% of the micro-CHP systems were available for at least 95% of the time”, claiming that most numbers of the occurred failures registered short periods of downtime. Hence, great performance has been achieved, under the circumstance that the project has involved the installations of fuel cell-based CHP system from 10 different companies, which have provided components and products with different level of readiness and maturity.

It is noticeable how most of the failures did not occur at stack level, whose downtime occurs with only 1% for PEMFC, and 2% for SOFC, as shown in Figure 1. The balance of plant presented the most sensitive part, accounting for the 64% of the total failures for PEMFC installations, and 55% for SOFC. The reformer systems have also accounted for important rates.

The Battelle Memorial Institute, with the funding and support of the United States Department of Energy (DOE) and Fuel Cell Technology Based Office, prepared a comprehensive report [7] evaluating a breakdown analysis of costs at component level for four different sizes of fuel cell-based CHP systems (PEMFC and SOFC), from 1 kW to 25 kW, in order to define a hypothetical market for these technologies, in absence of a commercially developed market analysis. The analysis received the support of important companies and research centers, such as Ballard, Hydrogenics, Watt Fuel Cell, Panasonic and the National Renewable Energy Laboratory. Both technologies have been analyzed by considering a natural gas adoption operation instead of a direct hydrogen feeding.

In order to take into account, the transition towards a large-scale production, the analysis has included the cost variations from an annual production volume of 100 units up to 50,000 units.

Figure 2 shows a re-arrangement of the above-mentioned analysis, for the PEM stack, summarizing the breakdown only for 1,000 units produced per year and 50,000 units produced per year. Large scale production will surely benefit the specific cost reduction: for 1 kW–size, the total stack cost can be reduced by more than 50%, dropping from 1,052.34

US$/kW to 460.09 US$/kW. The economy of scale effect is more visible for lower sizes, as for 5 kW the reduction resulted to be 27%. For every investigated scenario, the MEA presents the highest rate and share on the overall cost. Bipolar plate rates have almost an equal share coming from the anode and cathode sides (anode bipolar plates are slightly more expensive), while the anode/cooling gaskets contributes more than the cathode gasket to the overall gasket rate.

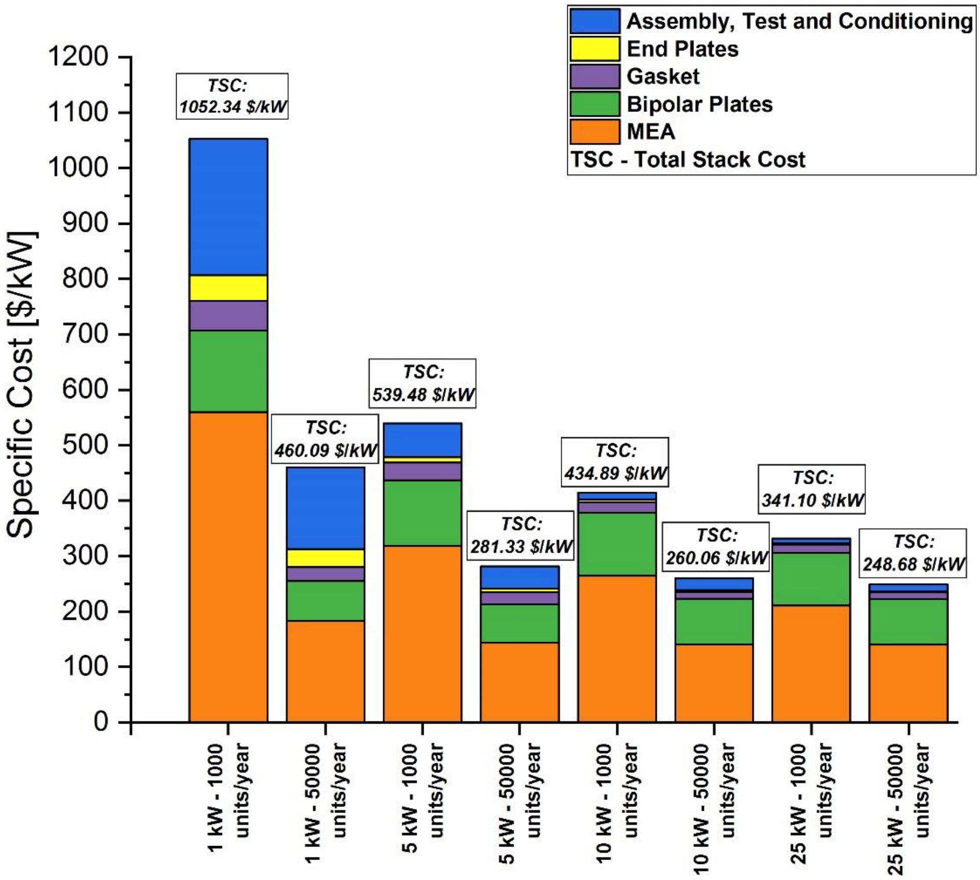

FIGURE 2: PEM FUEL CELL STACK POTENTIAL COST BREAKDOWN, RETRIEVED FROM [7]

In a similar way, the SOFC ceramic cell costs, shown in Figure 3, can be drastically reduced with a larger production scale, from 8,482.51 US$/kW for the small investigated size 1 kW, to 1,183.04 US$/kW, when the production increases up to 50,000 units per year. For lower production rates, glass ceramic sealing and laser weld account for the highest cost distribution rates, followed by the end plates and the ceramic cell itself. For higher production volumes, the highest contribution to the overall cost is given by the ceramic cells, while the other components and process benefit more from the economy of scale.

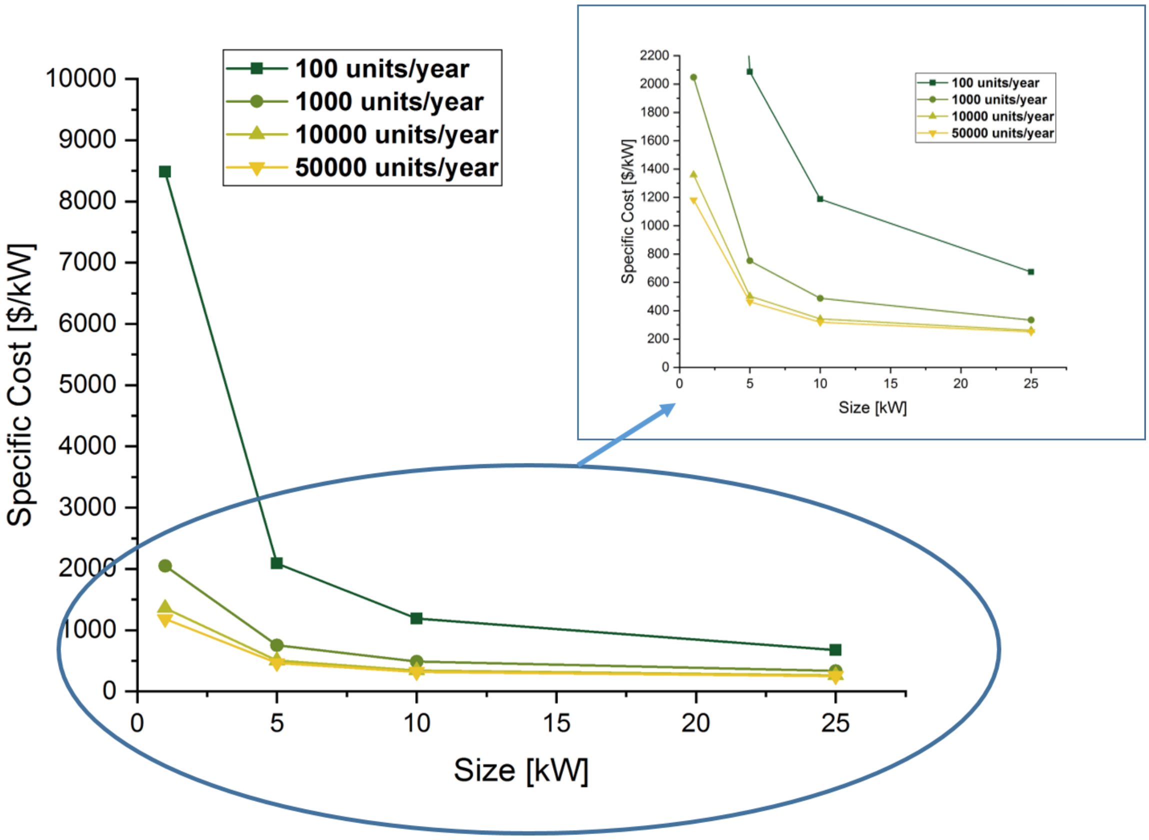

Figure 3: SOFC Ceramic Cell Potential Cost Breakdown, retrieved from [7]

As for the PACE/ene.field projects, the Battelle Memorial Institute has identified the balance of plant related components as the main contributors to the final costs. If for a PEM system the stack costs range between 9.2-14.7% of the total system cost for an annual production volume of 1000 units, the balance of plant components account for the 64.5-71.8%. Among all, the fuel processing area is the most expensive component area, with a share between 27-32% of the BOP cost distribution, followed by the AC and DC power components. Fuel processing is hence composed of a reformer, steam generator, and several reactors, such as water gas shift and PrOx reactors.

With a similar rent, SOFC BOP cost shares the highest rate (44.6-56.5%) for lower sizes, but for bigger installations, between 10 and 25 kW, the highest rate belongs to the CHP hardware components. In fact, thanks to their higher temperatures and fuel flexibility, the fuel processing related costs for the SOFC systems resulted to be significantly lower, benefiting from the natural process within the SOFC, the internal reforming, reducing the need of an external over-designed reformer. The presented results are in accordance with the more recent European Project deliverables for micro-CHP system: “at large-scale production, micro-CHP units can become economically competitive. The analysis found that fuel cell micro-CHP could become competitive with competing heating technologies at 5,000–10,000 units per manufacturer, in markets with attractive energy prices” [6].

It can be concluded that the balance of plant components, reformer and stack resulted to be the key elements of potential failures and cost reduction.

3. SYSTEM DURABILITY AND PERFORMANCE

The fuel cell size for stationary applications is strongly related to the power needed from the load. Since these sectors range from simple back-up systems to large facilities, the stationary fuel cell market includes few kW and less (micro-generation) to larger sizes of some MW.

The design parameters for the stationary fuel cell system differ for fuel cell technology (PEM, AFC, PAFC, MCFC, SOFC), as well as the fuel typology and supply. PEM and SOFC system are mostly used for micro-cogeneration applications and for small residential applications, while SOFC, PAFC and MCFC provide multi-energy services for large commercial and industrial applications.

Within a demonstration project in Europe [6], small PEM and SOFC systems have been installed and tested, and their performances are listed in Table 1.

Technology	PEM	SOFC
Electric capacity	0.3 – 5 kW	0.7 – 2.5 kW
Thermal capacity	1.4 – 22 kW	0.6 – 25 kW
System efficiency (LHV)	85 – 90 %	80 – 95 %
Electric efficiency	35 – 38%	35 – 60 %

TABLE 1: PEM AND SOFC SYSTEM PERFORMANCE, RETRIEVED FROM [6]

It is interesting how the real-life data and the on-field operation have presented a marked difference for SOFC system than the optimal conditions tested in laboratory: the average thermal efficiency resulted to be 46% (with a standard deviation between 30-59%) rather than 53%, while the electrical efficiency 37% (with a standard deviation between 28-47%) instead of 42%. Otherwise, the on-field operation of the PEM installed systems perfectly matched the laboratory data: 57% as average value for the thermal efficiency (with a standard deviation between 48-66%) and an electrical efficiency of 37% (with a standard deviation between 28-39%) [4].

A 2015 study from the Fuel Cell and Hydrogen Joint Undertaking outlined a potential analysis for several stationary fuel cell sizes and applications in Europe, in view of their commercialization. Main results are listed in table 2:

	Micro-CHP (PEMFC,SOFC)	Mini-CHP (SOFC)	Commercial CHP (SOFC)	Prime power 1.0 MW (SOFC,PEMFC)	CHP for Natural Gas (MCFC, SOFC,AFC)	CHP Biogas for industrial applications (MCFC, SOFC)
OPEX [k€]	0.5	0.85	6	60	800	30
CAPEX [k€/kW]	34	18.4	16.5	4.36	4.028	5.187
Installation, Control, Auxiliary [k€]	6.15	12.7	70.3	1200	1000	700
Added system [k€]	13.5	48.5	290	2500	2200	500
Stack [k€]	11.5	43.9	535.1	1500	2400	900
Maintenance [k€]	0.5	0.8	6	60	800	30
Stack Replacement [k€]	6.7	24	135.5	850	2150	790

TABLE 2: FUEL CELL SYSTEM PERFORMANCE, RETRIEVED FROM [8]

According to the different applications, the fuel cell systems have been categorized in different sizes. A micro-CHP system, as already discussed, is mostly installed by adopting PEM or SOFC, fed by natural gas, biogas or pure hydrogen. The installed capacity is usually 1 kW_{el} by cotemporally producing 1.45 kW_{th} of thermal power. These applications can reach 88% (36% of electrical efficiency and 52% of thermal efficiency), growing over time to 95% (42% electrical and 53% thermal), by being set both with a generic operating strategy and heat-driven operation. Capital cost reaches 34,000 € per installed kW capacity, and the stack replacement will account in operational cost up to 20% of the capex cost, considering a 10 years of life span with 2 replacements, improving to 15 years without replacement over time.

In a similar way mini-CHP (5 kWel and 4 kWth) and commercial CHP (50 kWel and 40 kWth) systems operate, by usually adopting SOFC system, with a capex cost respectively of 18.4 and 16.5 k€/kW. Prime power applications, up to 1 MW_{el}, operate in power-driven or load-following mode, achieving an electrical efficiency up to 48% growing to 51% over time. Two more categories can be derived: CHP for Natural Gas (up to 4 MWel and 1.1 MWth) and CHP Biogas for industrial applications (up to 400 kWel and 315 kWth).

The just mentioned data referred to 2015-2016. During the same period, in its Technology Roadmap Hydrogen and Fuel Cells [9], the International Energy Agency provided similar data on fuel cell micro co-generation systems, considering a fuel cell micro cogeneration system for commercial systems (up to 25 kW) with costs slightly less than 10000 US$/kW for the stack, and an electrical efficiency around 42%, and about 18000-19000 per kW for home systems. The reported lifetime ranged between 60,000-90,000 hours.

In June 2018, in the addendum to the Multi-Annual Work Plan, for 2014–2020 [10], the Fuel Cell and Hydrogen Joint Undertaking provided more data on CHP applications with fuel cell technologies. According to their analysis on the state-of-the-art for residential micro-CHP for single family homes and small buildings (0.3-5 kW), the 2017 CAPEX resulted to be 13,000

€/kW, being decreased since 2012, when the value was 16,000 €/kW. Maintenance costs drastically decreased, from 40 to 20 €-Ct/kWh, as well as the installation volume per unit, from 330 l/kW to 240 l/kW. Hydrogen Europe, in their draft of the Strategic Research & Innovation Agenda [11], re-elaborate those data and other forecasts up to 2030, for capital expenditure and maintenance costs, as shown in Figure 4 and Figure 5.

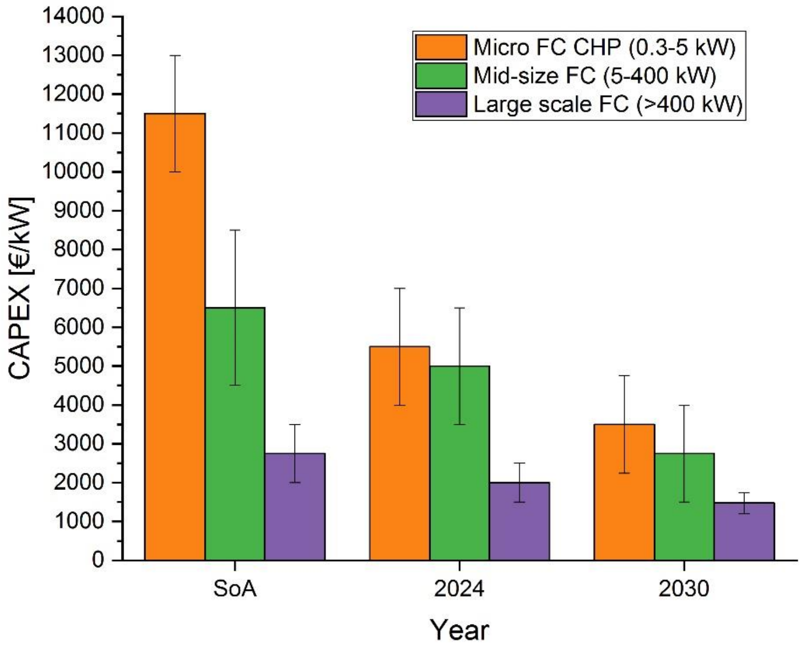

FIGURE 4: FUEL CELL CAPITAL EXPENDITURE FORECAST, RETRIEVED FROM [11]

Micro CHP systems, up to 5 kW, will decrease their investment cost, dropping to 3500 €/kW in 2030 and increasing the lifetime, in terms of years of operation, from 12 to 15, as well as the stack durability, from 40,000 hours to 80,000 hours. The availability of the plant is high in current situations, up to 97%, and it will increase to 98% in the future. The systems reliability will be strengthened even more, from 30,000 hours up to 100,000, decreasing also the maintenance costs, which will drop to 2.5 €-Ct/kWh in 2030. Electrical and thermal efficiency will be improved: several programs are aiming to improve performance in terms of efficiency. According to the prevision, electrical efficiencies will raise up to 65%, with a lower bound of 39%, while the thermal efficiency will maintain the upper bound (55%), while increasing the lower bound from 25 to 35%.

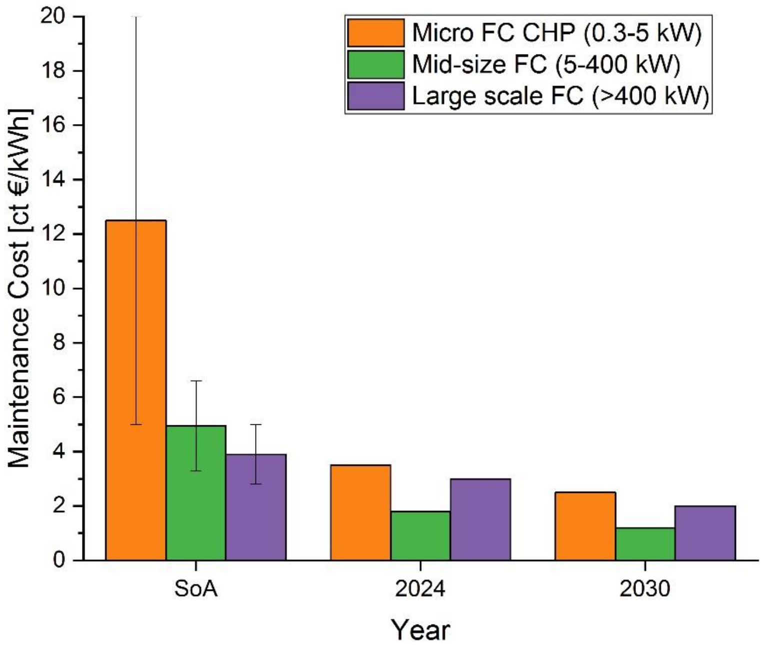

FIGURE 5: FUEL CELL MAINTENANCE FORECAST, RETRIEVED FROM [11]

For medium-size CHP systems, between 5 and 20 kW, a small progress can be found between 2012 and 2017: the CAPEX cost dropped from 6,000-10,000 to 4,500-8,500 €/kW. More improvements are expected. In 2030 the specific investment costs are expected to be within the range 1,500-4,000 €/kW. The lifetime of these systems will surely increase, from minimum of 6 years to 20 years, with a stack-durability more than doubled (from 30,000 hours to 80,000 hours). As for the micro-CHP systems, mid-size fuel cell systems reliability will be strengthened even more, up to 80,000, decreasing also the maintenance costs, which will drop to 1.2 €-Ct/kWh in 2030. The tolerated hydrogen content in natural gas in volume percentage, is expected to grow, too, up to 100%, reducing the cost of the components involved in the balance of plant, such as the reformer. The land use and the Carbon dioxide footprint are expected to decrease in 2030. The land use will drop from 0.15-0.08 square meter per kW of installed capacity, to 0.06.

Concerning the large-scale fuel cell systems, converting hydrogen and renewable methane into power in various applications (0.4-30 MW), data belonging to 2012 showed a capital expenditure cost of 3,000-4,000 €/kW, while it decreased to 3,000-3,500 €/kW in 2017. The current picture presents a value between 2,000-3,500 €/kW, and the economy of scale is expected to make the cost drop to 1,200-1,750 €/kW. Research and development actions are aiming to bring down the maintenance costs, too, from 5 to 2 € Ct/kWh, with a reliability up to 75,000 hours and a stack durability of 60,000 hours. Since most of these systems are adopting high temperature fuel cells, the current start-up phase and shutdown characteristics are close to 4 hours for a ramp from 0 to 100%. An improvement is also expected on this side, aiming to go to 100% in 1 minute.

Other fuel cell performance data are described in the appendix, with the estimation of the system durability that are maximally representative of common use cycles.

4. POTENTIAL FOR COST REDUCTIONS AND PERFORMANCE

Energy efficiency related actions could play an important role in achieving climate mitigation goals and sustainable development targets. In view of the United Nations Sustainable Development Goals (SDGs), energy and climate actions are treated as key targets[12].Following this train of thought, the main focus, also in fuel cell sectors, will continue to research the efficient conversion, probably by integrating several sectors, such as industrial waste gas recovery and utilization, power-to-gas, and alternative fuels (biogas and synthetic methane. As a strong support towards the hydrogen economy, the short-term adoption of fuel cells will be realized by feeding natural gas as primary source, above all for buildings and commercial applications, since the pay-back period is earlier achieved and more savings can be obtained compared to a pure hydrogen feeding. Thus, more research is needed to allow a greater hydrogen content in the fuel mixtures and in low-grade biomass, to decrease the cost of the fuel processing and achieve higher overall efficiency.

As seen in the previous paragraphs, the economy of scale will surely allow an important benefit for cost reduction and components reliability.

For small scale cogeneration systems (0.3-5 kW), several worldwide programs have been founded in different states, establishing one and more waves of early market penetration. The analyzed performance has shown how the field trials are ensuring a discrete economic return and high efficiencies; therefore, the next research steps must be canalized on stack cost reductions, strengthened supply chain and manufacturability improvements. For bigger sizes, demonstration projects are still needed, to increase the end-user’s perception towards these green and eco-friendly technologies, as well as to sustain private entities and companies to enter this new market. The Fuel Cell and Hydrogen Joint Undertaking are continuously promoting the transition towards bigger size, up to some MW, in order to move the technology towards important steps for energy storage and grid-stabilization, and drastically reducing the capital expenditures for a faster market penetration.

Integration with other sectors, such as off-grid installations and backup power configuration in telecommunication and data centers, will be surely needed in the next product generation.

For PEM fuel cells, the focus is on two disruptive solutions, through 'game changer' MEA and stack, with the goal to reduce the degradation phenomena and to facilitate the real-time monitoring and potential interventions, on field and during the component manufacturing, too, by including quality control procedure, automated sensors and defect searching. Balance of plant components, reformer and stack resulted to be the key elements of potential failures and thus research on them is a key enabler for cost reduction. Reduction in adopting critical raw materials and improved tolerance on Sulphur presence must be the new challenges, followed by the improvement for higher power density and stack tightness.

The other technology for deeply decarbonizing the stationary sector is represented by the SOFC systems. Being more flexible in the fuel feeding than the PEM fuel cell, main issues occur here within the system operation, start-up and shut-down operation, high-temperature corrosion and materials degradation.

Old and new materials need to be investigated, to guarantee a better tightness at the stack level, reducing fatigue and thermal failures, as well as a better temperature distribution and homogeneity during the transition phases. Feeding with biogas or low-quality biomass could also enable a faster market penetration and cost reduction at the operation level.

The possibility of reverse mode (SOFC/SOE) and co-electrolysis operations represent incredible potential for a carbon-free energy sector, even if the TRL of these technologies is still too low, and applied research actions are still recommended.

The DOE, in the United States, is also pushing forward the scaling up process, with the program H2@Scale [13]. Important achievements have been achieved in fuel cell sector. Investigations on platinum group metal free catalyst had great results and breakthroughs at ElectroCat, while FC-PAD is researching with good results at low platinum catalysts. These actions, with their results (for Co- and Mn-based catalysts), will surely conduct and drive the cost reduction and durability and performance improvement for the next PEM generation. In fact, "PGM-free catalysts achieved 27 mA/cm^2 compared to the 2016 baseline of 16 (mA/cm^2), a more than 65% improvement".

Los Alamos National Laboratory (LANL) has researched, investigated and developed innovative membranes and electrode ionomers. These new products will allow an extended temperature range for the fuel cell PEM operations (80-200°C) with an increased power density up to 1.5 W/cm^2. More research activities are listed in the appendix, and more can be found in one of the latest volumes of the Fuel Cells Bulletin Journal [14].

5. CONCLUSION

The present report has analyzed the technical performance of stationary fuel cells, both for micro-CHP and for large applications, as well as the financial state-of-art and the 2030 forecast.

The analysis on the micro-CHP systems, adopting PEM and SOFC, has shown as the balance of plant presented the most sensitive operation, accounting for the 64% of the total failures for the PEMFC installations, and 55% for SOFC. For a PEM system the stack cost ranges between 9.2-14.7% of the total system cost for an annual production volume of 1,000 units, while the balance of plant components account for the 64.5-71.8%. Among all, the fuel processing area is the most expensive component area, with a share between 27-32% of the BOP cost distribution.

SOFC BOP costs share the highest rate (44.6-56.5%) for lower sizes, but for bigger installations, between 10 and 25 kW, the highest rate belongs to the CHP hardware components. In fact, thanks to their higher temperatures and fuel flexibility, the fuel processing related costs for the SOFC systems resulted to be significantly lower.

Micro CHP systems, up to 5 kW, will decrease in investment costs, dropping to 3500 €/kW in 2030 and increasing the lifetime, in terms of years of operation, from 12 to 15, as well as the stack durability, from 40,000 hours to 80,000 hours.

Bigger sizes have also been investigated. Mini-CHP (5 kW$_{el}$ and 4 kW$_{th}$) and commercial CHP (50 kW$_{el}$ and 40 kW$_{th}$) systems operate by usually adopting SOFC system, with a capex cost respectively of 18.4 and 16.5 k€/kW. For systems up to 20 kW, the CAPEX cost dropped from 6,000-10,000 in 2012 to 4,500-8,500 €/kW in 2017. More improvements are expected until 2030, when the specific investment costs are expected to achieve values within the range 1,500-4,000 €/kW.

Prime power applications, up to 1 MW$_{el}$, operate in power-driven or load-following mode, achieving an electrical efficiency up to 48% growing to 51% over time. The current picture presents a value between 2000-3500 €/kW, and the economy of scale is expected to make the costs drop to 1,200-1,750 €/kW.

It is indeed important to track and investigate the performance of such systems, providing some interesting data on the state of art of the performance, as well as on some forecast in the up-coming years. In deeper detail, the present report lists a potential breakdown of the current costs of PEM/SOFC production for building applications over a range of production scales and representative specifications, as well as broken down by component/material. Inherent to the technology performance, a coincide estimation on FC system durability, efficiency, production, maintenance and capital cost are presented.

Finally, some potential for cost reductions and durability improvements, as well as strategies for improving performance of a number of the components of FC stacks, are presented.

Potential actions for cost reductions and research guidelines have also been presented, showing how cost reductions can be achieved with the economy of scale, but research and prototyping are still needed for bigger sizes (MW) to guarantee robustness and manufacturability for the next generations of fuel cell, in order to build a valuable supply chain and to increase the technology maturity and readiness level.

6. APPENDIX

6.1. FUEL CELL ENERGY PERFORMANCE

	Electric Size [kW]	Thermal Size [kW]	Investment Cost [€]	Applications	Electric Energy Efficiency [%]	CHP Energy Efficiency [%]	Ref.
SOFC	-	-	3500 €/kW	Commercial	-	-	[15]
MCFC	-	-	3500 €/kW	Commercial	-	-	[15]
PAFC	50–1000 kW (250 kW module typical)	-	-	Commercial	40-42	85-90	[16]
PEMFC	<1–100 kW	-	-	Commercial	30-40,0	85-90	[16]
MCFC	1–1000 kW (250 kW module typical)	-	-	Commercial	43-47	85	[16]
SOFC	5-3000,0	-	-	Home/Commercial	50-60	90	[16]
PEMFC	0,5-5	-	-	Home	35-45	75-90	[17]
PEMFC	0,5-5	-	-	Home	35-45	75-90	[17]
SOFC	0,5-5	-	-	Home	35-45	75-90	[17]
AFC	0,5-5	-	-	Laboratory	38-44	69-77	[17]
SOFC	0.75–250	0.75–250	-	Home/Commercial	45–60%	75-95%	[1,18]
PEMFC	0.75–2	0.75–2	-	Home	35-39	85-90	[1,18]
MCFC	>300	>450	-	Commercial	47	90	[1,18]
PAFC	100-400	110-450	-	Commercial	42	90	[1,18]
PEMFC	500,00	-	-	Commercial	40	-	[19]
PEMFC	1,00	-	-	Residential	34	-	[19]
PEMFC	440,00	-	-	Commercial	43	-	[19]
PEMFC	0,35	-	9000	Residential	33	-	[19]
PEMFC	0,75	-	20000-30000	Residential	37-40	-	[19]
PEMFC	1,5-5			Residential	34	-	[19]
PEMFC	0,70	-	20000-30000	Residential	35	-	[19]
PEMFC	0,75	-	36000	Residential	39	-	[19]
PEMFC	0,70	-	24500-28500	Residential	-	-	[19]
PEMFC	0,70	-	11800	Residential	38	95	[20]
PEMFC	0,70	-	-	Residential	38-39	94-95	[20]
SOFC	0,70	-	-	Residential	46,5	90	[20]
AFC	up to 250	-	200-700/kW	Commercial	50 (HHV)	-	[9]
PEMFC	0,5-400	-	3000-4000/kW	Commercial/Residential	32-49 (HHV)	-	[9]
PAFC	up to 11000	-	4000-5000/kW	Commercial	30-40 (HHV)	-	[9]
MCFC	kW to MW	-	4000-6000/kW	Commercial	>60 (HHV)	-	[9]
SOFC	up to 200	-	3000-4000/kW	Commercial/Residential	50-70 (HHV)	-	[9]

6.2. FUEL CELL MAINTENANCE AND LIFETIME EXPECTED

	Lifetime expected [hr.]	Degradation Rate [% per year]	Stack Replacement [year]	Other Data/Comment	Ref.
SOFC	-	0.6 % reduction in power output per 1000 h operation	5 yr. / 25% of the investment cost	Additional Capital Cost for Pressurized Fuel Cell 25 % increase on atmospheric Fuel Cell Cost	[15]
MCFC	-	0.6 % reduction in power output per 1000 h operation	5 yr. / 25% of the investment cost	Additional Capital Cost for Pressurized Fuel Cell 25 % increase on atmospheric Fuel Cell Cost	[15]
PAFC	40000	-	-	-	[16]
PEMFC	40000-50000	-	-	-	[16]
MCFC	15000	-	-	-	[16]
SOFC	40000	-	-	-	[16]
SOFC	20,000–90,000	1–2.5%	-	-	[1,18]
PEMFC	60000-80000	1%	-	-	[1,18]
MCFC	20000	1,5	-	-	[1,18]
PAFC	80000-130000,0	0,5%	-	-	[1,18]
PEMFC	70000	-	-	Panasonic	[20]
AFC	5000-8000	-	-	-	[9]
PEMFC	60000	-	-	-	[9]
PAFC	30000-60000	-	-	-	[9]
MCFC	20000-30000	-	-	-	[9]
SOFC	90000	-	-	-	[9]

6.3. POTENTIAL FOR COST REDUCTIONS & RESEARCH ACTIONS FOR SOFC

Research Objectives	Methods and Technique	Key findings and Bottleneck	Ref.
Investigation of integration methods with fluctuating energy patterns	Dynamic modeling of MINLP in GAMS	The system can provide savings up to 11.3%. Such a system is more suitable in houses where electricity and heating loads are comparable	[21]
Comparative assessment with conventional heating systems	Energy consumption is estimated using HOT2000 building simulation program	1–2 kW_{el} systems are economically feasible for the considered case	[22].
Integration of SOFC with an SNC battery to reduce primary energy consumption	Thermal integration to exploit SOFC residual heat for the battery stand-by feeding	SOFC able to operate without major load variations. Thermal and electric system efficiency up to 80% and 7%, respectively; primary energy savings up to 4000 kW h/y/kW.	[23]
In SOFC mode the station is fed by mixtures rich in H2 with CO2, CO, N2, while in SOE mode it is operated as electrolysis for H2 production and co-electrolysis for combined H2-CO production	Data acquired experimentally and produced using specific ad hoc-developed algorithms	Experimental tests the overall energy mapping of the SOFC-SOE system. The developed algorithms and the experimental data analysis can become good decision-making tools for the manufacturers of these energy systems	[24,25]
Design of a control unit for future prototype systems	0-dimensional model to reproduce logic of an onboard control system	Additional fuel is required for the off-gas burner, resulting to system efficiency reduction. Fuel utilization factor must be regulated to avoid low operating temperatures.	[26]
Model calibration using empirical data	Experimental program under a series of controlled boundary conditions	Calibrated empirical coefficients only valid within the ranges of independent variables examined in the experiments.	[27]
Optimization of operating conditions of power modules and determination of potential design bottlenecks	3D thermochemical model modeling	High temperature gradients in the cell due to the high current densities, or insufficient cooling air, must be avoided to increase the lifetime of the cell. Increasing coolant flow rate increases pressure drop, which in turn increases electricity consumption of actuators	[28]
Evaluation of performance of five different system designs	A cell model is scaled-up to predict voltage–current performance characteristics (EES)	Maximum efficiency is achieved when cathode and anode gas recirculation is used along with internal reforming of methane. Heat loss can have an adverse impact on system efficiency	[29]
Emission and economic performance assessment of a commercially- available system	Technoeconomic analysis	Support mechanisms such as electrical export, feed-in tariff and export tariff, are required in order to achieve competitive results	[30]

Assessment of building cogeneration and polygeneration systems	Transient whole-building and energy system simulation tools	Compared to conventional technology, significant energy and carbon savings are achieved.	[31]
Prediction of system performance	Quasi 2D model (Aspen Plus)	The parameters with the highest influence on system performance are cell voltage, fuel flow rate and stack inlet air temperature.	[32]

6.4. POTENTIAL FOR COST REDUCTIONS & RESEARCH ACTIONS FOR PEMFC

Research Objectives	Methods and Technique	Key findings and Bottleneck	Other Data/Comment	Ref.
Decrease system exergy losses and improve performance	Exergo economic analysis of system with thermal storage, absorption chiller (EES)	Fuel cell voltage can significantly affect system exergy cost, which decreases by increasing heat source temperature	Nafion-PEMFC-based micro-CHP system	[33]
Assessment of a system with membrane reactor with different natural gas qualities	Technoeconomic analysis	Adoption of the most diluted natural gas must be selected for the reactor to perform at high efficiency with any NG composition	Nafion-PEMFC-based micro-CHP system	[34]
Performance analysis of a PEMFC-floor heating system	HEN optimization w/ pinch analysis; sizing of floor heating system	System performance is mostly affected by HEN and fuel cell electrical performance.	Nafion-PEMFC-based micro-CHP system	[35]
Evaluation of system to improve efficiency	Steady state modeling; system optimization with Thermoptim	Novel operating strategies and new system designs can be suggested in the future	Nafion-PEMFC-based micro-CHP system	[36]
Model calibration using empirical data	Model discretized to represent 12 sub-systems for simulating thermal and electrical performance	The study did not consider improvements for catalysts and membranes.	Nafion-PEMFC-based micro-CHP system	[37]
Investigation of effect of key operating parameters on system performance	Energy and exergy analysis; system simulation (Aspen Plus)	Stack cooling loop is impractical for a model that must be calibrated using empirical data	Nafion-PEMFC-based micro-CHP system	[38]
Evaluation of system performance for a typical Danish single-family household	Simulation in LabVIEW to provide ability of Data Acquisition of actual components	Inaccuracies in fuel processing subsystem occurred due to the lack of appropriate semi-empirical functions. LabVIEW simulation creates a great difficulty in adjusting and modifying highly complicated models, due to its graphical modeling nature	PBI-PEMFC-based micro-CHP system	[39]

Apply parametric studies to reach to achieve high cogeneration efficiencies	Evaluation of different synthesis/design and operating strategies (EES)	Further validation with experimental data is needed. System model is very complex, with a high number of decision and other variables, which make the parametric study very limited and constrained	PBI-PEMFC-based micro-CHP system	[39]
System design and optimization	GA optimization strategies (EES)	Objective function for the optimum design configuration results to a 20.7% increase. A more in-depth study of the water knockout/condenser stage might be necessary to minimize local losses.	PBI-PEMFC-based micro-CHP system	[40]
Maximization of net electrical efficiency, and HEN cost minimization	GA (EES) and process integration using MINLP (GAMS)	High efficiencies are accomplished; net electrical efficiency and total system efficiency are 35.2% and 91.1%, respectively; HEN total annual cost is US$8147	PBI-PEMFC-based micro-CHP system	[41]
Formulation of an improved operating strategy	Application of actual annual load profile; analysis of efficiencies, heat dumping; electricity import/ export (EES)	Lower heat-to-power ratios avoid high thermal surpluses throughout the whole annual operating load profile	PBI-PEMFC-based micro-CHP system	[42]
Improvement of thermo-economic performance with the coupling of a heat pump	Heat-led operation; system optimization for every different load (EES).	Average net electrical efficiency and average total system efficiency are 0.380 and 0.815, respectively. Cost analysis shows that certain synergies are necessary to allow the proposed system to make an entry to the energy market.	PBI-PEMFC-based micro-CHP system	[43]
Investigation of system response at transient electrical and heating loads	Dynamic modeling (MATLAB-Simulink)	Absolute lowest consumption of each component could not be determined, but it was possible to reach the lowest overall methane consumption. Waste heat should be minimized with proper sizing of the fuel cell and optimization of the control strategy	PBI-PEMFC-based micro-CHP system	[44]
Modeling of system and validation with experimental data	Modeling of system with flow-sheet simulator ASPEN HYSYS	System requires a high degree of heat integration and optimization of its configuration and operating conditions	PBI-PEMFC-based micro-CHP system	[45]

Determination of optimal operating parameters considering the impact of degradation	Multi-objective optimization (MATLAB)	Degradation affects primarily the electrical efficiency and power generation throughout the system lifetime.	PBI-PEMFC-based micro-CHP system	[46]

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