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Status on Demonstration of Fuel Cell Based Micro-CHP Units in Europe[▲]

E. R. Nielsen¹, C. B. Prag^{1*}, T. M. Bachmann², F. Carnicelli², E. Boyd³, I. Walker³, L. Ruf³, A. Stephens⁴

¹ Technical University of Denmark, Department of Energy Conversion and Storage, Frederiksborgvej 399, 4000 Roskilde, Denmark

² ELFER (European Institute For Energy Research), Emmy-Noether-Strasse 11, 76131 Karlsruhe, Germany

³ Element Energy, 78 Margaret Street, London W1W 8SZ, United Kingdom

⁴ Energy Saving Trust, 30 North Colonnade, Canary Wharf, London E14 5GP, United Kingdom

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Abstract

Micro combined heat and power (micro-CHP) systems can efficiently provide private homes or small commercial buildings with both heat and electricity. The European industry is ramping up demonstration of fuel cell based micro-CHP units in the EU projects ene.field and PACE. Systems based on solid oxide fuel cells (SOFC) and polymer electrolyte membrane fuel cells (PEMFC) have been demonstrated. More than 1,000 units have been tested in 10 European countries in the years 2012–2017. In the coming 5 years, additionally 2,500 units will be deployed *via* the EU funded program PACE. These field trials have been accompanied by analyses of end-user satisfaction, environmental impact, and costs involved.

The end-users participating in the field trials had a very positive perception of the fuel cell micro-CHP technology. The environmental impact of fuel cell micro-CHP was compared to that of heat pumps and gas condensing boilers in a life cycle assessment (LCA). The micro-CHP units have a better environmental performance than these competing technologies in all the analyzed use-cases.

Today, the capital costs of fuel cell based micro-CHP are significantly higher than that of traditional heating technologies. However, as serial production begins, economies of scale will cause the costs to drop substantially and the micro-CHP can become economically competitive.

Keywords: Fuel Cell, Fuel Cell Application, LCA, Micro Combined Heat and Power, PEMFC, SOFC


1 Introduction

Over the last years, an increasing number of fuel cell based micro combined heat and power systems have been demonstrated in field trials in Europe [1]. Besides the practical experience from installation and operation of the systems, a number of reports have considered pathways for commercializing and possible business models for stationary fuel cells in Europe [2, 3].

A fuel cell can efficiently produce both electricity and heat from natural gas. This can be utilized in a combined heat and power (CHP) unit. Units with an electric capacity below 50 kW are usually referred to as micro-CHPs [4]. Typical systems with capacity up to 5 kW are suitable for both residential

use and small commercial buildings. For micro-CHP applications, two main types of fuel cells are used: solid oxide fuel cells (SOFC), which operate at high temperatures (600–850 °C) and are made from ceramic materials (“solid oxide”) and polymer electrolyte membrane (PEM) fuel cells which operate at lower temperatures (60–160 °C) and are based on polymer materials. Fuel cell micro-CHP units allow for significant increases in the efficiency of heat and power production compared with traditional heating appliances, eliminate the transmission losses of grid distributed electricity and, hence, they may bring a reduction in the overall primary energy consumption of the households [5].

[*] Corresponding author, cbrpr@dtu.dk

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More than 1,000 small stationary fuel cell systems for residential and commercial applications have been demonstrated in 10 European countries in the project ene.field [1]. This project has been Europe's to date largest demonstration project for fuel cell micro-CHP systems. In an on-going project PACE, where units are currently being deployed, an additional 2,500 unit will be demonstrated.

Other European demonstration projects have previously been carried out: Danish micro combined heat and power (50 units, 2006–2014 [6]), the German Callux project (500 units, 2008–2015 [7]), SOFT-PACT (65 units, 2011–2015 [8]) and more. In the upcoming years, the German programme KFW433 will enable large-scale deployment of fuel cell micro-CHP units by subsidies to the end customers.

The record holder for deployed units is the Japanese subsidized deployment effort of the ENE-FARM systems [9, 10]. In the period from 2009 to December 2016, more than 198,500 of these units were installed. This deployment effort has a target of 300,000 units installed by 2020.

As for the previous projects, the ene.field and PACE projects are important steps on the path from demonstration of prototypes to reaching a commercial mass market. These are currently the most coordinated efforts in demonstrating fuel cell micro-CHP technology in Europe. As the ene.field project has now been finalized, results from the field trials and the corresponding analyses have been concluded. The main results and conclusions from this project are presented in this paper.

2 Technical Performance

Over the course of the ene.field project, a number of analyses were made based on data collected from the units installed in the project. In this section, key results relating to technical performance and end-user perception of the technology are highlighted.

Table 1 Summary of the characteristics of products demonstrated in the ene.field project. The thermal capacity includes the gas condensing boiler for backup/peak load. Efficiencies are under optimal conditions and have been calculated from the lower heating value (LHV) of the used natural gas [1].

Fuel Cell Technology	PEM	SOFC
Number of units	443	603
Number of manufacturers	5	5
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%

More than 1,000 units were installed in residential and small commercial buildings in the ene.field project between 2012 and 2017. These units were operating and collecting data for 1–3 years. The first units were installed in 2013 and installation numbers were below 200 units, until September 2015 where a ramping up of installations began. By September 2017, all of the final 1,046 units had been installed.

Units with very different characteristics from 10 manufacturers have been deployed, see Table 1 and Figure 1. In total 603 SOFC units and 443 PEM units have been demonstrated with more than 5.5 million hours of operation in total and more than 4.5 million kWh electricity produced. The 1,046 units installed have a total capacity of approximately 1155 kW of distributed power generation.

The technical performance of all micro-CHP units in the field trial was monitored. All “issues encountered” (failures) were reported by manufacturers based on eight pre-define failure categories.

The system availability was calculated based on information regarding system off-time in connection with issues. When an issue caused the system not to be able to produce

Elcore 2400	Dachs InnoGen	Cerapower FC10 Logapower FC10	Vitavalor	SteelGen	Galileo 1000 N	Vaillant G5+	PEMmCHP G5	BLUEGEN	ENGEN 2500	Inhouse 5000+
										
HT PEM	LT PEM	SOFC	PEM	LT SOFC	SOFC	SOFC	LT PEM	SOFC	SOFC	LT PEM
300W	700W	700W	700W	700W	1kW	1kW	2kW	2kW	2.5kW	5kW
Natural Gas	Natural Gas	Natural Gas, Gas	Natural Gas	Natural Gas	Natural gas + Biogas	Natural Gas	Natural Gas + Biogas	Natural Gas	Natural Gas	Natural gas + Biogas + H ₂
Wall	Floor	Floor	Floor	Wall	Floor	Wall	Floor	Floor	Floor	Floor
Elcore	SenerTec	Bosch Thermotechnik	Viessmann	Ceres Power	Hexis	Vaillant	Ballard Power	Solid Power		RBZ

Fig. 1 Summary of the characteristics of products demonstrated in the ene.field project. Thermal capacity includes the gas condensing boiler for backup/peak load. Efficiencies are under optimal conditions and calculated from the lower heating value (LHV) of the used natural gas, reproduced from [1].

power or not able to start-up, it was considered as unavailable. Systems were also considered unavailable during planned service activities, such as scheduled maintenance. The system was available at all other times than when the above specified criteria applied. The parameter “availability” was specified as the percentage of hours where the system was available compared to the total number of hours where it possibly could have been available.

A detailed analysis of the availability was made for 67 units, see Table 2. Of these systems, 45% experienced no failures in the first year of operation and an availability of 100%. Hence, 55% had 1 or more failures. However, the vast majority of these failures were only for short periods of time; 90% of the micro-CHP systems were available for at least 95% of the time [1].

These results show that the technology is well on its way to very high robustness. In previous projects, such as Callux availability has been reported as high as 96% [7]. For the field trials in the PACE project, the goal is availability of 99%. The results from ene.field clearly show that this should be feasible.

Of the total failures encountered, only 1–2% of them relate to the core fuel cell stack component, see Figures 2 and 3. 86% of the experienced failures are not related to the fuel cell module and its core components (stack, reformer and inverter). Of the remaining 14%, the reformer and inverter were responsible for 12% of the issues encountered for both technologies (SOFC and PEM). As the field trial involved systems from 10 different manufacturers, the results include both less and more mature products. The high availability and the low number of failures caused by the fuel cell stack show that from a technical point

Table 2 Number of failures during the first year of operation and the corresponding availability, after [1].

Number of Failures	Percentage of Installed Systems	Availability / %
0	45%	100.0
1	19%	98.2
2	24%	98.3
> 3	12%	86.9

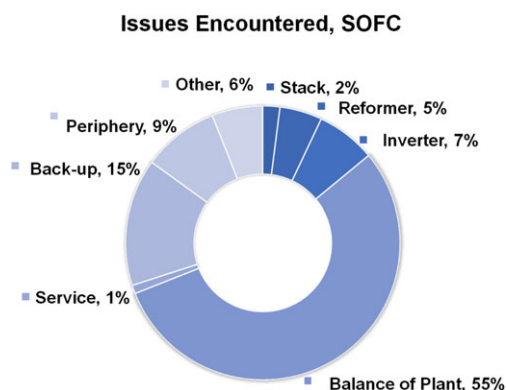


Fig. 2 Distribution of the causes of failures for SOFC based micro-CHP in the field trial, adapted from [1].

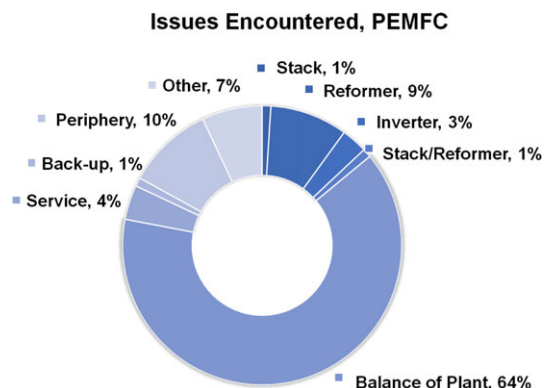


Fig. 3 Distribution of the causes of failures for PEM based micro-CHP in the field trial, adapted from [1].

of view, the fuel cell based micro-CHP technology is ready for large market penetration.

3 End-user Satisfaction

Two surveys to collect information about end-user expectations and experience with the fuel cell micro-CHP systems were conducted during the ene.field field trial. One was collected from the end-users before installation of the micro-CHP system and one was collected after approximately one year. This approach was chosen to detect any changes in end-user perception over the first year of operation.

The end-users participating in the ene.field project were very positive about the micro-CHP technology. In general, they were very satisfied with all the aspects of their micro-CHP systems. It is especially worth noting that their perception of the environmental profile of the technology was entirely positive. However, two areas with room for improvement were identified: running costs and ease of use of the technology.

End-users were asked how satisfied they were with their micro-CHP systems with respect to a number of criteria. The questions included satisfaction with (i) comfort and warmth, (ii) heating and hot water production, (iii) electricity generation, and (iv) overall satisfaction.

The survey responses showed that the overall satisfaction was very good (an average score of 3.9 out of 5). Satisfaction with comfort and warmth, space heating, hot water production, and environmental performance scored higher than the average (4.3 out of 5), while the satisfaction with running costs and ease of use/controllability scored slightly lower than average (3.5 and 3.6, respectively), see Figure 4.

The lowest scoring aspects of the systems are potential barriers to wider adoption of micro-CHP systems. Although running costs depend on wider political and economic factors and therefore may be difficult for the manufacturers to influence, improving the ease of use of the systems is something which is within the control of manufacturers. This could be down to improved system design, system documentation or after-sales support [11].

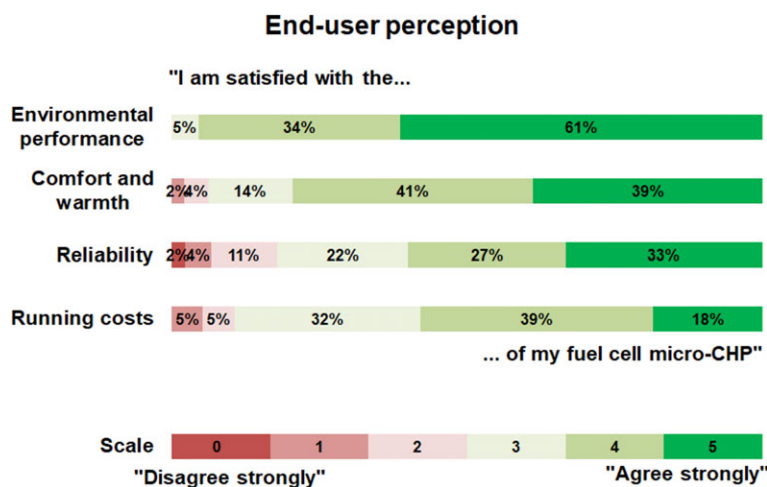


Fig. 4 Results from end-user surveys, after [11].

4 Assessing Environmental Performance

The environmental performance of fuel cell micro-CHP units has been assessed by means of a life cycle assessment (LCA) compliant with the HyGuide guidance document for fuel cells [12] as part of the ene.field project. Various use cases were analyzed, varying notably in terms of a home's space heating demand depending on occupancy (single *vs.* multi-family homes), insulation level (existing *vs.* new or renovated buildings) and climate zone (Southern, Central or Northern Europe). The fuel cell systems (including a backup gas condensing boiler) were compared with other technologies, i.e., air-water heat pumps (for single family homes) and stand-alone gas condensing boilers (for all use cases). In all use cases, the home has a hot water storage and is connected to the electricity grid (taken to correspond to the ENTSO-E electricity mix according to [12]). All comparisons consider systems that provide the same function, i.e., they provide the same amount of heat and electricity for a given use case. The impacts of different electricity replacement mixes were investigated, varying in terms of the carbon intensity of the electricity that is replaced by the micro-CHP.

For the analyzed use cases and under the assumptions made, the main findings are:

- (i) Life cycle greenhouse gas (GHG) emissions of the fuel cell micro-CHP units are lower than for the gas condensing boiler and the heat pump in all the investigated use cases.

- (ii) Micro-CHP units generally lead to lower air pollutant emissions compared with the alternative systems as the electricity produced by the fuel cell causes less emission than the replaced electricity from the grid (based on the power sources considered in this analysis).

- (iii) The micro-CHP efficiency and the full-load hours of operation throughout the year are the main characteristics that influence the final LCA results. The full-load hours vary depending on the micro-CHP capacity relative to the home's demand, on the operation pattern, such as periodic off-time due to regeneration of the fuel cell, and whether the operation of the unit is heat-led or electricity-led.

- (iv) The environmental gain of micro-CHP is more evident in multi-family home use cases than for single family homes, because of higher electricity production replaced in the grid (resulting from more full-load hours at a higher rated capacity).

- (v) The emission savings by heat-led micro-CHPs (relative to gas condensing boilers) are governed by a) a low heat demand of the home and thus a low utilization of the backup boiler, and b) a high carbon intensity of the electricity production replaced.

Figure 5 shows the life cycle CO₂-equivalent emission savings of a 0.7 kW_{el} heat-led FC micro-CHP compared to a gas condensing boiler as a function of the annual full-load hours (FLH) for one of the use cases (a not renovated single-family home located in Central Europe). The FLH is a measure of

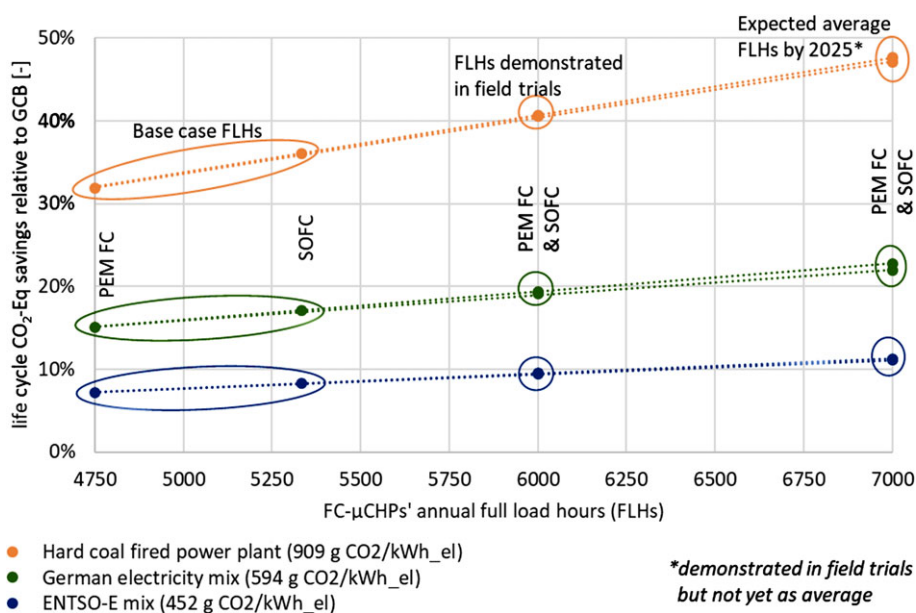


Fig. 5 Life cycle CO₂-equivalent emission savings by fuel cell micro-CHP relative to a gas condensing boiler (GCB) as a function of the annual full-load hours (FLH) of the micro-CHP. Results are shown for different power production mixes that are replaced by fuel cell electricity. The use case shown is existing (i.e., not renovated) single family homes located in central Europe, which is typical for the ene-field units demonstrated in field trials [13].

how much the unit is utilized. The FLH correspond to the number of hours that a unit should operate at full load in order to generate the same amount of electricity as actual produced. The results are shown for 3 different replacement mixes, i.e., for three levels of carbon intensity of the electricity that is replaced by electricity from the micro-CHP. All electricity from the FC micro-CHP is assumed to be exported and replacing electricity from the reference mix. All of the electricity demand of the house is assumed to be covered by the ENTSO-E grid mix.

The CO₂-equivalent savings results shown in Figure 5 are given for a base case, a revised case and a projected case. The base case of 4,750 FLH for PEM units and 5,333 FLH for SOFC units, originally defined in the beginning of the project, was revised during the project based on FLH demonstrated in the ene.field project to 6,000 FLH for both technologies [14]. It was found that under these assumptions the base case gave savings of 548 (7%) and 632 (8%) kg CO₂-equivalent pr. year and the revised case 713 (9%) and 722 (10%) kg CO₂-equivalent pr. year for PEMFC and SOFC, respectively, when replacing the ENTSO-E mix in the grid. Under assumptions of a German hard coal replacement mix savings went from 2,740 (36%) to 3,093 (41%) kg CO₂-equivalent pr. year for SOFC and 2,425 (32%) to 3,084 (41%) for PEMFC when revising the FLH [14].

5 Life Cycle Cost Analysis

At today's capital and maintenance costs, fuel cell micro-CHPs are significantly costlier than traditional heating technologies. However, as serial production begins, economies of scale can be realized, and previous studies suggest that these costs are expected to drop significantly [2]. Over the last few years, deployment of micro-CHP units in Europe has gone from 10s of units to thousands, and several European manufacturers have made considerable steps towards commercialization. In turn, this has led to updated estimates of costs and technical improvements that can be made as production scales increase.

A study of the life cycle cost of fuel cell micro-CHP was made based on the updated manufacturing costs and the performance projections [15]. It was compared with incumbent technologies. A number of key European markets were analyzed, based on typical household heat demands as well as gas and electricity price data. The main conclusions are [15]:

- (i) Increase in production volume leading to reduced production costs (economies of scale) is crucial to the economics of micro-CHP.
- (ii) Micro-CHP performs best economically in countries where there is a wide spread between the retail gas and electricity prices.
- (iii) Fuel cell micro-CHP units are best suited to high run-hour applications, where there is sufficient heat demand to use all heat produced.
- (iv) 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.

- (v) Subsidies can improve the near-term economics of micro-CHP units, but depending on the subsidy design, could have the same effect on competing technologies.

6 Installation Barriers and Markets

In the field trials, a large amount of time and effort is spent providing the information needed for the administrative preparation of each site (e.g., information to grid operators, approvals, etc.). Forms have not been standardized, and in some cases a vast number of documents have to be completed. The lead time for completing the paper-work varies significantly between countries. In some countries, approvals may typically take 2–3 months.

Administrative barriers for grid connection and accessing support schemes persist and, thus, hinder large-scale deployment of micro-CHP systems [11, 16, 17].

Germany has proved to be the most successful market in terms of ene.field deployment numbers. The majority of the units deployed have been installed in Germany – more than 750 units. This is mainly due to the presence of financial support schemes. Funding from the national support schemes helps decrease the investment costs and thereby favors the ramping up of the installation numbers. Furthermore, the German market is characterized by a better understanding of the technology by the end customers, installers and energy services suppliers as well as a favorable spark spread (difference between electricity price and gas price) which makes micro-CHP more beneficial. This trend is expected to continue as more units are installed as part of future deployment activities with national or European support.

The PACE project is the natural next step following the ene.field project. The project will install more than 2,500 micro-CHP units in 11 countries in the period 2016–2021. The focus areas are: Product innovation and cost reduction, supply chain development, policy collaboration, demonstration and verification of primary energy savings, and testing grid benefits. As of the end of March 2018, 872 units have been sold and 116 units installed as part of the PACE project. The PACE project is expected to facilitate a transition to higher production volumes in the order of 10,000 units per year in Europe after 2020.

7 Conclusion

In the years 2012–2017, the ene.field project has demonstrated more than 1,000 fuel cell based micro-CHP units in 10 countries. From a technical point of view, the fuel cell based micro-CHP technology is ready for large market penetration. Over long periods of time, the availability of the units to the end-user has been above 99%. Of the failures encountered, only 1–2% of them were caused by the fuel cell stack itself.

The end-user participating in the ene.field project were very positive about the micro-CHP technology. In general, they were very satisfied with all aspects of their micro-CHP systems, especially the environmental performance of the technology.

If a large-scale market uptake of micro-CHP systems is realized, this can help the EU fulfil energy policy aims and climate commitments. In the investigated use cases and for the assumptions made, the life cycle emissions of GHG of a micro-CHP are lower than those of a gas condensing boiler or a heat pump. The use of micro-CHP units also leads to lower air pollutant emissions compared with the alternative systems.

At today's capital and maintenance cost levels, micro-CHPs are significantly costlier than traditional heating technologies. As serial production begins, economies of scale will cause the costs to drop significantly. A life cycle cost analysis has shown that the micro-CHP technology can become economically competitive. Subsidies can improve the near-term economics of micro-CHP systems, and may be crucial for the technology to reach the mass market.

Germany has proved to be the most successful market in Europe in terms of deployment numbers. Funding from the national support schemes helps decrease the investment costs and thereby favors the growth of the market.

A lack of a common framework of European standards is seen as a large hindrance to the market uptake. Countries use international and European standards but supplement with their own versions. Moreover, the forms for approval of installation lack standardization and the process may be complex and lengthy.

The German support programme KfW433 will facilitate the commercialization of the fuel cell based micro-CHP technology in the coming years. As a follow-up to the ene.field project, the field demonstration of fuel cell micro-CHP systems in Europe continues with the EU funded project PACE where 872 units have been sold and 116 units installed as of the end of March 2018.

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