

Advancing Europe's energy systems: Stationary fuel cells in distributed generation

A study for the Fuel Cells and
Hydrogen Joint Undertaking



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Executive Summary

Stationary fuel cells can play a beneficial role in Europe's changing energy landscape

The energy systems across Europe face significant challenges as they evolve against the backdrop of an ambitious climate agenda. As energy systems integrate more and more generation capacity from intermittent renewables, numerous challenges arise. Amongst others, Europe's energy systems of the future require new concepts for complementary supply, such as efficient, distributed power generation from natural gas. At the same time, significant investments to modernise the electricity grid infrastructure are needed. Moreover, long-term storage solutions become a growing priority to ensure permanent power supply, e.g. power-to-gas. Moreover, Europe puts greater emphasis on energy efficiency in order to save primary energy, reduce fuel imports and increase energy security.

Against this background, distributed generation from stationary fuel cells promises significant benefits: In distributed generation, fuel cell systems exhibit particularly high energy efficiencies (electrical efficiency of up to 60%, combined efficiency in cogeneration of more than 90%), thereby attaining considerable primary energy savings whilst avoiding transmission losses. The technology virtually eliminates all local emissions of pollutants. When using natural gas and thereby building on existing infrastructure, stationary fuel cells can substantially reduce CO₂ emissions as highly efficient conversion of low-carbon natural gas replaces central supply from a still predominantly fossil-fuelled electricity mix. Depending on the fuel used and its source, the technology can potentially eliminate CO₂ and other emissions altogether – e.g. when fuelled with pure hydrogen produced from water electrolysis using electricity from renewables. With its flexible modulation capabilities and high efficiencies at partial loads, the technology shows strong potential for grid balancing in the context of a power mix with more intermittent renewables and electric heating solutions like heat pumps.

Despite these considerable benefits and the wide array of potential use cases for application, the commercial role of fuel cell distributed generation in Europe remains limited so far. At the same time, the industry has gained traction in other advanced countries, such as Japan, South Korea and the United States where stationary fuel cells already commercialise. The biggest hurdle for the European industry is to reduce production costs to offer competitive pricing and thereby successfully capitalise on superior performance in terms of efficiency, emissions and economics.

This study outlines a pathway for commercialising stationary fuel cells in Europe

The present study outlines a pathway for commercialising stationary fuel cells in Europe. It produces a comprehensive account of the current and future market potential for fuel cell distributed energy generation in Europe, benchmarks stationary fuel cell technologies against competing conventional technologies in a variety of use cases and assesses potential business models for commercialisation. Considering the results of the technological and commercial analysis, the study pinpoints focus areas for further R&D to sustain innovation and provides recommendations for supportive policy frameworks.

The study has been sponsored by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a public-private partnership of the European Commission, the fuel cell and hydrogen industry and a number of research bodies. Compiled by Roland Berger Strategy Consultants, it builds on an interactive approach involving a coalition of more than 30 players from the EU stationary fuel cell stakeholder community.

The European stationary fuel cell industry can serve a variety of use cases

The European landscape of stationary fuel cells for distributed generation has grown increasingly rich and diverse in terms of the solutions for different use cases that the industry can provide. The European market for stationary fuel cells can be divided into three different market segments: residential,

commercial and industrial. One of the most mature clusters of fuel cells comprises integrated micro-CHPs in the power range of 0.3 to 1.5 kW_{el} to supply heat and electricity to 1/2-family dwellings or single flats in apartment buildings. European manufacturers appear to be broadly ready for large-scale diffusion from a technical perspective. Some companies already sell products mostly under public support programmes; the rest participates in ongoing large-scale field tests like the ene.field project. In terms of commercial buildings, the European fuel cell industry has not yet fully developed products in a medium power range of 5 to 400 kW_{el}. European products are predominantly in the R&D and prototype phase (especially below 100 kW_{el}); some begin field tests. In terms of industrial applications for prime power or CHP beyond 400 kW_{el}, the readiness of the European fuel cell industry is mixed; some players are already bringing products to the market, with support of global know-how especially from the US.

Stationary fuel cells have large market potential across Europe

Building on existing infrastructure, gas-fuelled fuel cell CHPs can potentially supply heat and power to every building with a connection to the gas grid as their primary market. Moreover, buildings may find a switch of their heating fuel attractive when fuel cell CHPs can offer a beneficial value proposition. Considering new buildings as well as typical replacement cycles in the building stock, the total primary and conversion market for heat-driven, integrated fuel cell mCHPs for residential 1/2-family dwelling amounts to more than 2.5 m units annually in Germany, the United Kingdom, Italy and Poland combined. In the same markets, the annual potential for heat-driven, gas-fuelled fuel cell CHPs in apartment and commercial buildings is estimated at 10.8 GW_{el} installable capacity. As an example for industrial applications, large prime power fuel cells could target 1.4 GW_{el} of installable capacity at data centres in the same countries, whilst large fuel cell CHPs face a market 5.8 GW_{el} of already installed gas-fuelled CHP capacities in pharmaceutical and chemical production facilities.

Rigorous technology benchmarking reveals the potential benefits of fuel cells for different users

In environmental terms, gas-based integrated fuel cell CHPs can substantially reduce CO₂ emissions when compared to a state-of-the-art gas condensing boiler and grid power supply – depending on the specific use case, operating strategy and power mix in the respective European market (e.g. ca. 30% less CO₂ emissions for a partially renovated single-family house in Germany under the current power mix). Emissions of pollutants like NO_x or SO_x can be virtually eliminated when a fuel cell replaces conventional heating technologies. In economic terms, stationary fuel cells are currently uncompetitive from a Total Cost of Ownership perspective due to high capital cost. However, they are already highly competitive in terms of variable energy cost alone given their high efficiencies. Consequently, stationary fuel cells will offer a beneficial value proposition to users if capital cost can be reduced to allow for an acceptable payback period. According to first-hand industry data, sufficient production volumes can significantly reduce cost and make systems economically competitive. With growing volumes, competitiveness could initially be reached with higher-end heating and CHP technologies over the next years. To jump-start this first commercialisation phase, a supportive policy framework is necessary.

Policy makers should initially support commercialisation under clear industry commitments

In order to reap the substantial benefits of stationary fuel cells at different levels, the industry has to undertake significant efforts to bring down cost and improve quality, whilst the policy framework has to be supportive. For the mature segments, financial instruments or incentives would support the volume uptake to jump-start commercialisation whereas additional funding for dedicated R&D activities should be channelled towards demonstration projects in promising, but less mature segments. Specifically, the study recommends a market introduction programme with investment support for fuel cell micro-CHPs targeting residential buildings, further funding for R&D and demonstration projects for medium-range fuel cell CHPs targeting commercial buildings, and project-based financial support for the very diverse industrial applications of stationary fuel cells. Immediate priority for volume uptake is on investment support for mCHPs and project-based support for fuel cells targeting the industrial segment.

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PART I:

Summary Report

Introduction

This study outlines a pathway for commercialisation of stationary fuel cells in distributed generation across Europe. It has been sponsored by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a public-private partnership between the European Commission, the fuel cell and hydrogen industry and a number of research bodies and associations. The FCH JU supports research, technology development and demonstration activities in the field of fuel cell and hydrogen technologies in Europe. The study explores how stationary fuel cells can benefit users, how they can be brought to the market, what hurdles still exist, and how their diffusion may foster Europe's transition into a new energy age.

The study builds on an interactive approach involving stakeholders who play a key role in the roll-out of fuel cell distributed generation in the European Union, namely a coalition of more than 30 stakeholders of the European stationary fuel cell community. In recent years, the European landscape of stationary fuel cells for distributed generation has grown rich and diverse in terms of the solutions for different market segments and use cases that the industry can provide. Not only can fuel cells meet fairly homogeneous customer requirements as in residential buildings (e.g. fuel cell mCHP systems with an electrical capacity between 0.3 and 5 kW_{el}) but the industry also delivers tailor-made solutions in a power range of several MW for special industrial applications such as breweries or wastewater treatment plants. Different stationary fuel cell systems use a wide portfolio of different technology lines and are currently at different points of the product lifecycle – some being ready for large-scale market introduction, whilst others concentrate on research and development as well as demonstration projects.

The study paints a long-term picture of distributed generation from stationary fuel cells in Europe. Overall, the study analyses four different European focus markets for stationary fuel cells (Germany, United Kingdom, Italy and Poland), examines six different generic fuel cell systems and defines 45 specific use cases for benchmarking these systems against more than 35 competing technologies in distributed generation – and all that over a time horizon of 35 years until 2050 under three different scenarios for how the future energy landscape in Europe might evolve.

Stationary fuel cells

Stationary fuel cells efficiently convert pure hydrogen, biogas, natural gas or other gaseous hydrocarbons into electricity and heat – often in cogeneration, i.e. combined heat and power generation. Fuel cells directly transform primary chemical energy from the fuel into final electrical and thermal energy thereby achieving higher efficiencies than combustion-based technologies that burn fuel to generate first mechanical and then electric or thermal energy (i.e. conventional power plants). In terms of fuel, some fuel cell technologies require pure hydrogen as a fuel (for instance produced by steam

reforming natural gas or through water electrolysis), whilst others can use hydrocarbons directly, e.g. natural gas or biogas. In terms of essential technical set-up, all fuel cells typically comprise an anode, a cathode and an electrolyte. As hydrogen and oxygen flow into the fuel cell, the electrolyte causes charges to move between anode and cathode. During a chemical reaction, electrons are drawn from the anode to the cathode through an external circuit, thereby producing direct-current electricity. In the process, only excess hydrogen, heat and gaseous water are emitted. Cogeneration systems use the waste heat in the process and thereby further increase efficiency of the system, i.e. the ratio of total final energy (electrical and thermal) to total primary energy, i.e. the chemical energy of the fuel. Units are typically set up in a modular way by combining a number of cells to a stack with the desired capacity.

Already today, stationary fuel cell systems are used in a wide range of applications, ranging from small CHP systems for 1/2-family dwellings to multi-MW power plants that supply entire districts with electricity and heat. The majority of fuel cells in the European industry portfolio are integrated CHP solutions – some of which primarily supply heat to buildings (i.e. are heat-driven) with power as an add-on product, whilst others position themselves as base-load power generation units (i.e. are power-driven) with excess heat as an add-on product. Stationary fuel cells are a distributed generation technology, i.e. they produce power and heat – by and large – at the site of the consumers in question and for the purpose of their immediate supply with energy.

Roles and benefits of stationary fuel cells in Europe's future energy landscape

In a nutshell, the study concludes that stationary fuel cells are a highly efficient technology to transform today's fossil fuels and tomorrow's clean fuels into power and heat – with the potential to be one of the enablers of Europe's transition into a new energy age. Figure 1 illustrates the main rationale behind the roles and benefits of stationary fuel cells in Europe's future energy landscape.

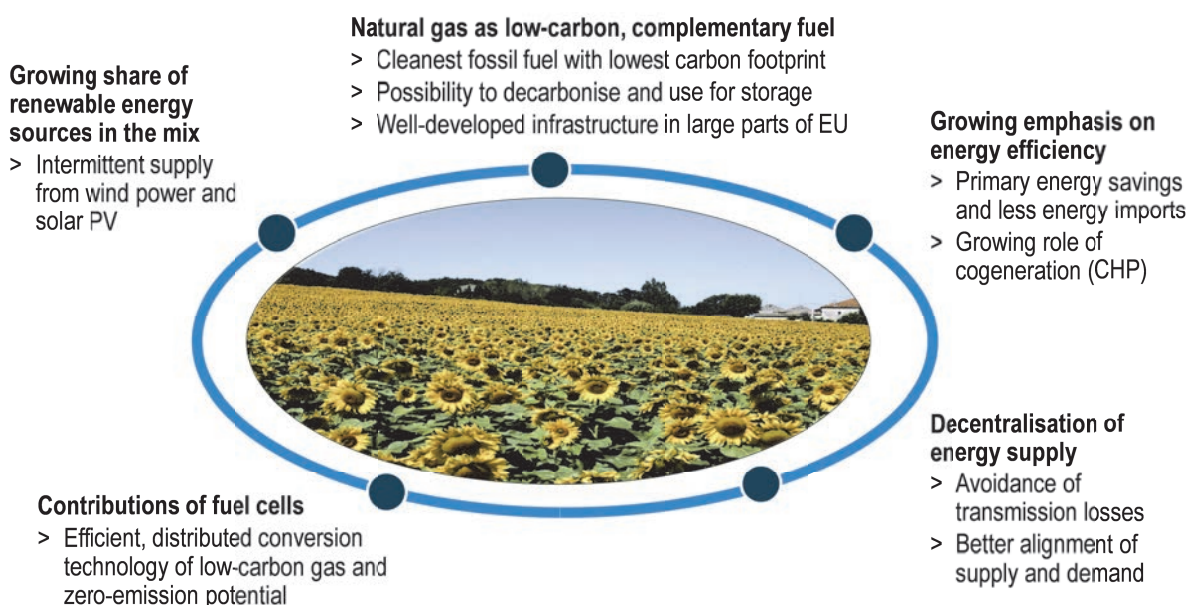


Figure 1: European energy trends, policy framework and general market conditions

Europe's future in energy: The landscape becomes increasingly renewable

The energy landscape in Europe changes fundamentally. Determined to assume a global leadership role in combating climate change, European countries have in recent years intensified their efforts to reduce the emissions of greenhouse gases through higher energy efficiency and more carbon-free generation. More and more countries are fully embarking on the transition towards an energy system largely based on renewable energy sources (RES) like wind, solar or biomass in order to meet their ambitious environmental objectives. On this path, political commitment appears strong – stronger maybe than in other industrialised nations. By the year 2020, the EU is committed to raising the share of renewable energy sources in final energy consumption to 20%, lowering greenhouse gas emissions by 20% compared to 1990 levels and achieving a 20% increase in energy efficiency. The roadmap for moving to a low-carbon economy in 2050 prescribes the long-term goal of cutting emissions to 80% below 1990 levels through domestic reductions alone, with milestones of the order of 40% by 2030 and 60% by 2040 along the way. According to the Commission, the EU could be using around 30% less energy in 2050 than in 2005 by moving to a low-carbon society.¹

The overhaul of Europe's energy system is already visible – particularly as concerns the increasing role of distributed generation and RES. Today's electricity landscape is already moving rapidly towards distributed generation capacities (photovoltaic panels, wind turbines, CHP plants and others). In Germany, renewable energy comes from 1.3 million different suppliers combining a total capacity of 53 GW, thereby representing 32% of a total installed generation capacity of 165 GW. Total renewables contributed nearly 25% of gross power generation in 2013 as installed capacity in solar PV has increased by more than a factor of 80 over the past 10 years. At nearly 11 GW by the end of 2013, the UK has now installed 14 times the capacity in wind power that it had ten years ago.²

With an ever rising share of RES in the energy mix, several challenges arise to guarantee the security of supply to all European citizens at every point in time. Particularly tough challenges are the long distances between production and consumption, the growing number and diversity of different suppliers and the structural intermittency of solar and wind power. Whilst the former require substantial investments in the expansion of power grids, the latter inevitably calls for complementary technologies, fuels and storage solutions to provide permanent, secure energy supply.

Outlook for natural gas: "here to stay" as a source of primary energy for the foreseeable future

Given its suitability as an enabler for more and more generation from RES, natural gas will most probably play a key role in Europe's future energy mix and stationary fuel cells are a highly attractive technology to convert it to heat and power at low emissions and with high efficiencies. Several characteristics of natural gas as a fuel and the benefits of gas-conversion technologies make gas an attractive complementary element of renewables in the energy mix of the future:

Natural gas is already the cleanest of all fossil fuels with the lowest carbon footprint of fuel. Natural gas causes direct CO₂ emissions of 202 g/kWh_{fuel} – substantially less than the ca. 300 g/kWh_{fuel} for oil, the 339 g/kWh_{fuel} for hard coal and considerably less than the 404 g/kWh_{fuel} for lignite.³ Due to the high efficiency of gas conversion technologies such as stationary fuel cells, the edge of natural gas in terms of its carbon footprint in electricity and heat generation is even larger. Moreover, recent studies find that even life-cycle greenhouse gas emissions for electricity produced from unconventional gas sources like

¹ Cf. European Commission (2014)

² Cf. BP (2014)

³ Cf. UBA (2013)

shale gas are on a par with emissions from conventional gas and on average about half those of coal. In short, natural gas is commonly regarded as the greenest fossil fuel to complement intermittent renewables in Europe's future energy mix.

Additionally, there are options for greening the gas grid and further decarbonising it along with the power mix. Firstly, the feed-in of biogas into the European gas grid is expected to grow in the coming years. As the number of German biogas feed-in stations has more than quadrupled over the past 5 years, the feed-in of biogas into the gas grid has risen from 102 m to 638 m standard cubic metres annually.⁴ Secondly, the green gas portfolio is growing with further gases from renewable fuels, such as bio synthetic gases. Finally, the methanation of hydrogen generated by electrolysis of water using renewable electricity has the potential to become a long-term game changer that further decarbonises the gas grid. Additionally, fuel cells can also be used to clean up natural gas and thus lower emissions.

Most importantly, gas may be the only viable long-term storage solution to back up seasonally intermittent electricity supply from solar and wind power. Batteries, pumped storage and other conventional storage technologies have natural limits in terms of storage capacity and horizon, as well as regarding potential for considerable expansion in Europe. To the contrary, power-to-gas in which surplus power from solar and wind energy is converted to natural gas through electrolysis and methanation would build on existing gas infrastructure. Current pilot projects deliver the first results in terms of improving the efficiency and economic viability of the technology.

In Europe, natural gas boasts of a well-developed infrastructure for transmission, distribution and storage in most parts of the continent – albeit to varying degrees. Countries with high degrees of infrastructural development are, amongst others, the UK, the BENELUX countries, Ireland, Germany, Austria, Italy and Spain. In the Netherlands, more than 90% of households have access to natural gas. In many urban areas across the continent, gas is already within reach for almost all buildings.⁵

Gas conversion technologies may technologically complement intermittent power supply from renewables, especially with technologies with high flexibility, good modulation capacities and short ramp-up times. This is true for conventional gas conversion technologies like combined-cycle gas turbines and gas-fired engines, but even more so for stationary fuel cells which still operate very efficiently at partial loads and thus tolerate a significant degree of modulation. In times of high supply from intermittent renewables, distributed stationary fuel cells can reduce their power output and feed-in in order to help balance the grid.

Globally, natural gas remains a relatively abundant fuel as conventional resources are further exploited and upstream players increasingly tap unconventional sources like shale gas. Moreover, the trade in Liquefied Natural Gas (LNG) is increasing. In this context, Europe – as a major gas importer – is increasingly diversifying its supplier base by tapping new domestic sources, opening alternative supply basins via new pipelines (e.g. the Southern Gas Corridor) and increasing LNG absorption capacities.

All in all, its advantages as a low-emission fuel with green potential, the well-developed conversion technologies and the large European infrastructure base suggest that natural gas is "here to stay" for the foreseeable future. It remains an energy source of choice with its ability to cover the transition period between a carbon-intensive energy profile and one that is low-carbon or eventually even carbon-free.

⁴ Bundesnetzagentur (2015)

⁵ Fawcett, Tina, Lane, Kevin et al. (2000)

Distributed generation: Decentralised natural gas solutions will likely grow, especially CHP

As a fuel for power and heat, natural gas is becoming increasingly important, especially in distributed Combined Heat and Power (CHP) generation that is close to or even on site of residential, commercial and industrial consumers.

In recent years, central gas power plants have struggled to remain economically attractive. In many European markets, they fail to reach the necessary annual operating hours as they come under merit-order pressure from increasing generation from renewables, more competitive commodity prices for hard coal and lignite and a low price of CO₂ emission certificates on the European Trading Scheme (ETS). Consequently, highly efficient gas-fired power plants have had to shut down in recent years and utilities have tended to shy away from new investments in large conventional power plants with long lead times and payback periods as revenue flows become increasingly unpredictable – at least in the absence of a capacity-based market for permanently available supply.

District heating remains an option only for urban areas. District heating remains an attractive central-generation solution (e.g. with CHP based on natural gas) and will likely remain a technology of choice in urban areas (specifically urban centres) albeit not in all European countries alike. On the one hand, utilities still succeed in committing customers to long-term contracts and on the other hand, investments in generation capacities succeed due to the predictability of revenues from selling heat during the heating periods. Nevertheless, for consumers with an interest in their own power production, distributed CHP is a highly interesting option.

Distributed generation can follow the specific heat and power demand of the consumer on site, whether it is coming from stationary fuel cells, gas engines or even small turbines. Operating hours can be forecasted more reliably, tend to be usually very high (e.g. more than 6,000 hours per year in heat-driven residential or commercial applications). Fuel cell mCHP systems driven by the heat demand of households have already demonstrated between 6,000 and 8,000 operating hours per year in ongoing field tests across Europe. Specific supply meets specific demand. Distributed generation produces heat and power when the consumer in question needs it – whilst centralised and decentralised production from renewables occurs irrespective of actual demand. In distributed CHP generation that is heat driven, decentralised systems moreover generate constant electricity output during the heating period (e.g. from September to April for central and northern Europe) when other consumers heating with electric systems especially need it, e.g. residential homes equipped with heat pumps. Whilst electric heating devices can put a strain on power grids in cold periods of the year, heat-driven distributed CHP systems like stationary fuel cells consume less grid power during this period and, furthermore, feed surplus electricity into the system for everyone else to take up.

Moreover, there is a growing interest in independent power supply. As the fluctuating power supply from renewables increases, transmission and distribution system operators have to substantially increase their efforts to maintain the stability in the grid and keep power frequency within a close range of 50 Hertz. Whilst European power grids are still amongst the most reliable in the world, critical infrastructure providers and businesses with sensitive applications are becoming increasingly interested in decoupling the availability of electricity from the grid and becoming more independent. In Germany, the total number of businesses with more than 20 full-time employees that produce their own electricity on site has more than doubled from 2008 to 2012. Already, CHP is the technology of choice in industrial distributed generation; in Germany, the share of CHP in industrial distributed generation has risen from 56% to 70% from 2008 to 2012.⁶

⁶ DESTATIS (2013)

Distributed generation means decoupling from rising grid power prices. The most relevant energy price indicator today with regard to fuel cell powered and really any gas-fuelled distributed generation is the spark spread as a rough margin indicator for gas-to-power/heat generation. In recent years, electricity prices have risen in many European countries, whilst gas prices have been kept in check – partly due to long-term, oil-indexed supply contracts, the increase of gas-to-gas competition and overall falling demand from central gas-fuelled power generation. On an EU level the electricity prices for household and industrial consumers currently range between 14.9 and 20 EUR ct per kWh, whilst the natural gas prices for household and industrial consumers are between 5 and 6 EUR ct. The implied spark spread, assuming an efficiency factor of 49.1% for gas-to-power conversion, as is standard in topical literature, then ranges from 4.8 to 6.6 EUR ct on EU average per kWh.⁷ On a country basis and depending on the specific use case the spark spread may lie at a much higher figure, however. With growing spark spreads, distributed generation from natural gas becomes more attractive – a general European trend that appears likely for the foreseeable future.

Complementary to distributed energy technology for power generation such as solar PV, heat-driven fuel cells in combined heat and power generation help further decarbonise the energy mix on the side of heat production. In CHP, they provide both electricity and heat thereby improving the efficiency of providing both and moreover improving the efficiency compared to traditional CHP technologies. Indeed one of the key strengths of fuel cells is that the excess heat from producing electricity can be used at the location where it is needed.

Growing importance of energy efficiency: Stationary fuel cells are highly efficient

European governments are putting more and more emphasis on consuming less energy in the first place, as the continent transitions towards a new energy system. The EU has reaffirmed its commitment to further moving towards a cleaner, more efficient energy system by endorsing a target of 27% for the year 2030. EU institutions seek to achieve new opportunities for European businesses, affordable energy bills for consumers, increased energy security through a reduction of imports and a positive impact on the environment.

The building sector will see significant energy efficiency measures. In the European building stock, improved insulation to reduce the overall energy demand in the building sector (especially for heat) will likely become the focal point of energy efficiency measures. Political will is strong at the European level and at the level of key Member States to boost energy efficiency measures such as better insulation in the building stock through renovation and higher energy efficiency standards for new buildings. Many new buildings (e.g. new built 1/2-family dwellings) across Europe are already built up to such high efficiency standards that they barely require any external energy for heating at all.

Energy efficiency is also a technology issue. Distributed generation as such is already more fuel efficient than central generation. Distributed power and heat generation at the site of consumption means that there are no losses from energy transmission and distribution networks. Losses in the power transmission and distribution grid amount to 5-8% in Western Europe and are even higher in Eastern Europe where grid infrastructure tends to be older.⁸ Thus, the avoidance of power transmission losses raises the efficiency edge of distributed generation compared to large central power plants.

Gas-fuelled technologies like stationary fuel cells, combustion engines or turbines of various sizes are the most energy efficient power conversion solutions. Of all of them, stationary fuel cells have the highest electrical efficiency potential, with European suppliers of Solid Oxide Fuel Cells (SOFCs)

⁷ Eurostat (2014)

⁸ World Bank (2014)

already offering systems with 60%_{el} efficiency, the same as the most efficient gas turbines currently in operation. Some fuel cell suppliers see more potential for raising electrical efficiency even further. Even fuel cell CHP systems that are designed to primarily supply heat to a building and generate power as a by-product do so with much higher electrical efficiencies than engines or turbines, at a given thermal efficiency.

From a primary energy point of view, cogeneration of power and heat is generally more efficient than separate generation. Consequently, CHP has been a technology solution that has been supported by governments across Europe – through investment subsidies, power production premiums and feed-in tariffs. As of 2011, the European countries with the highest share of CHP in gross power generation were Denmark (46%), the Baltic countries (10-47%), the Netherlands (32%) and Italy (20%) – even though most CHP capacity is nowadays still installed in central power plants.⁹ Stationary fuel cells for distributed generation are the most efficient CHP technology available, with combined efficiencies of more than 90%.

Summary of technology review: The main benefits of the fuel cell

Figure 3 summarises the major benefits of stationary fuel cells cited above and revolving around the role they can play in the context of Europe's future energy system:

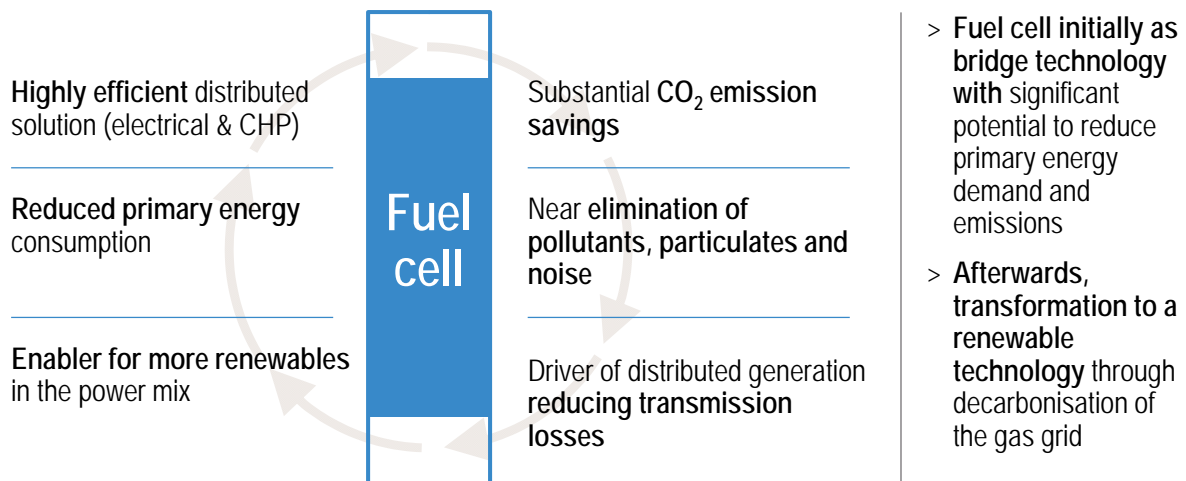


Figure 2: Stylised overview of main benefits of stationary fuel cells

Saving primary energy – Stationary fuel cells have extremely high electrical efficiencies – there is hardly any other distributed generation technology that has the potential to convert primary energy into this much electricity. When used for the cogeneration of heat and power, combined efficiencies outperform other CHP technologies. As primary energy savings become more and more desirable, CHP and fuel cell CHP in particular will become the technology of choice.

Saving CO₂ emissions – With their high efficiency, fuel cells in distributed generation can yield substantial CO₂ savings in the building sector and various industrial applications – especially when building on the natural gas infrastructure in the transition period towards a carbon-free European power mix and even beyond given the zero-emission potential of the fuel cell technology.

Eliminating local emissions – Stationary fuel cells can nearly fully eliminate local emissions of pollutants like NO_x and SO_x as well as particulates – a particular advantage for urban population centres

⁹ Eurostat (2014)

where local emissions tend to become a drain on the standard of living and governments are already putting regulatory limits in place. Moreover, stationary fuel cells emit exceptionally little noise.

Enabling renewables – Fuel cells are an effective technology to play a complementary, enabling role in a power mix that is increasingly dominated by intermittent renewables. Generally speaking, heat-driven CHPs will have seasonally complementary operating cycles to solar power and hence produce power as a by-product of heat when electric heaters like heat pumps need it.

Capitalising on existing infrastructure – Natural gas remains a part of Europe's energy mix for the foreseeable future and already boasts a well-developed, existing infrastructure for transmission, distribution and storage. Stationary fuel cells can capitalise on this infrastructure and become an important new technology, e.g. for gas-heated buildings in the building stock.

Boosting distributed generation and power security – As an innovative solution, fuel cells have the potential to boost distributed generation and thereby further unlock the systematic benefits of a less centralised energy system. For the individual user, stationary fuel cells bear the benefit of increased power security, especially in parts of Europe with structurally weak power grids or for power-sensitive industrial applications.

Commercialising stationary fuel cells in Europe

Scenarios for Europe's future energy landscape

The study develops three different macroeconomic scenarios for Europe's future energy system from now until 2050, in which the commercialisation of stationary fuel cells succeeds to varying degrees. The three scenarios were developed jointly with a designated group of topic experts from industry, government and civil society organisations inside and outside the coalition.

They enable us to view three possible settings in 2050 within which distributed generation evolves to varying degrees according to how strongly the policy commitment to a low-carbon energy mix has developed. We take a closer look at possible trajectories for the policy framework and energy market environment and at how these factors influence the relevant prices (electricity, natural gas, carbon) that in turn shape the market potential for fuel cell powered distributed generation. In these scenarios, the spark spread of electricity to gas is a decisive price indicator for fuel cell attractiveness as it indicates the level of attractiveness of producing power from natural gas.

The three scenarios are:

- Scenario #1 – "Untapped Potential" with a low degree of distributed generation
- Scenario #2 – "Patchy Progress" with a moderate degree of distributed generation
- Scenario #3 – "Distributed Systems" with a high degree of distributed generation

We consider the "Patchy Progress" scenario the most likely. It describes a 2050 where there is moderate, yet regionally fragmented policy support for distributed generation. The share of renewables has increased leading to an urgent but yet unmet need for a pan-European smart grid for enhanced energy balancing. Energy efficiency has increased, yet further potential remains. The price of carbon has somewhat recovered and the spark spread is moderate for both household and industrial consumers. Here the 2050 prices for electricity range from 18.2 to 24.5 EUR ct for industrial and household consumers respectively. For gas the forecasted price range stretches from 5.7 to 7.5 EUR ct for industrial and household consumers respectively. The price of carbon has recovered significantly in

this scenario and measures approx. 16-33 EUR/t. In Europe, ETS reform has led to an expansion of its coverage and now it encompasses virtually all industries.

Alternatively, the "Untapped Potential" scenario describes a 2050 where policy commitment to distributed generation – both renewables and non-renewable yet carbon-efficient forms like gas-fuelled fuel cells – is lacking. Energy efficiency potential has not been realised and fossil fuels still make up most of the energy mix. The price of carbon has failed to recover and the spark spread for electricity and gas prices is low or even negative. The "Distributed Systems" scenario depicts a 2050 where the policy commitment to distributed generation is high, as it has emerged as the source of choice for generating power and heat. This is reflected in a very high share of renewables in the energy mix that is seamlessly integrated thanks to a highly developed pan-European grid. The price of carbon is sufficiently high to incentivise the utilisation of low-carbon energy generation solutions as well as investments in energy efficiency.

General commercialisation trajectory for stationary fuel cells

The "Patchy Progress" scenario is the basis for the following analysis and recommendations, whilst the two other possible trajectories are covered by sensitivity analyses.

In Europe, the commercialisation of distributed generation from stationary fuel cells will likely occur in three stages. Ultimately, the technology has mass-market potential – with different speed and scope of diffusion in different market segments that mostly results from different maturities of fuel cell technologies and markets today. Figure 3 illustrates two partial commercialisation pathways.

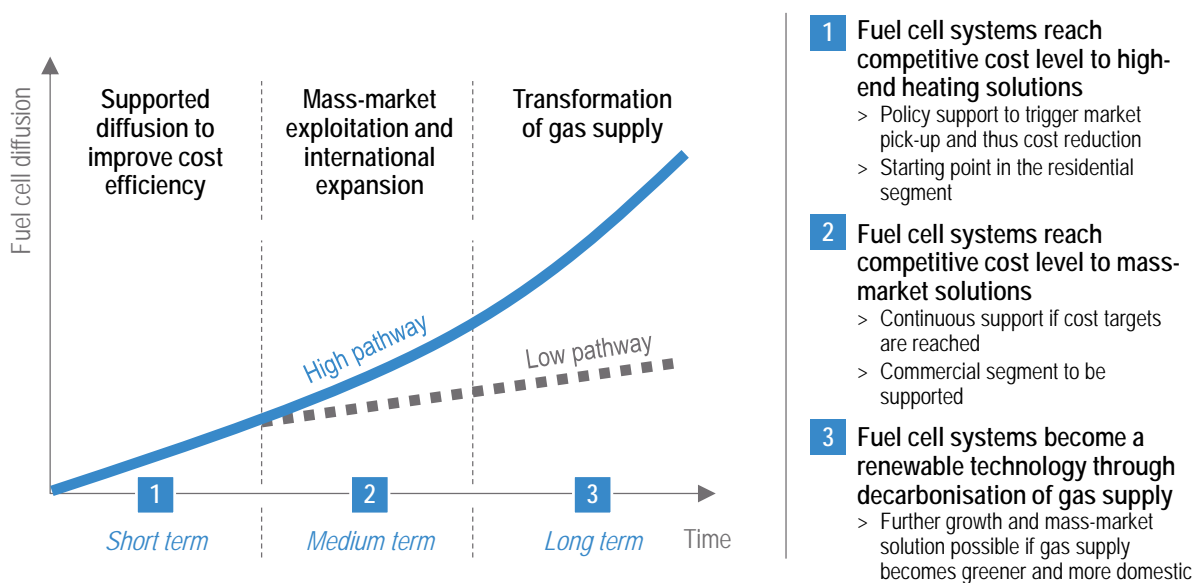


Figure 3: Possible commercialisation trajectories of stationary fuel cells in Europe [schematic]

Short-term diffusion: Initially, industry will have to overcome substantial cost hurdles and achieve further technical improvements – in some cases to reach market readiness and in other cases to enable full industrialisation. In this short-term phase, the industry requires public support schemes, e.g. through targeted funding of R&D and market introduction programmes like investment subsidies. Here it is important to go one step beyond funding innovation and enabling the industry to reach the first milestone of cost reduction. Over the short-term, fuel cells will have a significant impact on reducing emissions and primary energy consumption in the specific use cases where they are deployed.

Mid-term expansion: Subsequently, after initial cost reductions have been achieved and public support schemes gradually phase out, the industry can explore European markets at large. In the high pathway,

fuel cell mCHPs of ca. 1 kW_{el} can tap the significant potential of all gas-heated residential buildings with standardised, mass-market products. Novel financing mechanisms for the purchase or installation of fuel cells (e.g. leasing or contracting) will help commercialisation as the technology will likely remain comparatively expensive as a more valuable and feature-rich product. The most substantial emissions savings will be realised over the medium term when volume picks up and the diffusion of low-carbon, fuel cell power makes a large difference to a power mix that is only in the process of decarbonising. At the same time, the larger-scale deployment of fuel cells begins to clearly show the benefits of the technology regarding its complementary role with renewables. In a low pathway however, fuel cells will gain less traction and continue to compete in a high-end niche.

Long-term disruption: As the power mix decarbonises further and further over the long term, the greening of the natural gas grid provides a long-term perspective of the sustained commercialisation of stationary fuel cells. With the increased share of renewable gas from biomass, synthetic sources and power-to-gas, the fuel cell can position itself as the technology of choice for efficiently converting the greener gas to power and heat. In a low pathway of market diffusion, the fuel cells struggle to maintain a comparative environmental advantage over other distributed generation technologies and a decarbonising power mix – e.g. due to a less effective decarbonisation of the gas mix.

Addressable market potential and demand drivers for stationary fuel cells

Stationary fuel cells have a wide range of applications where they can have a significant impact on local savings of emissions and primary energy. The market can be divided into three different market segments – residential, commercial and industrial – as illustrated in Figure 5:

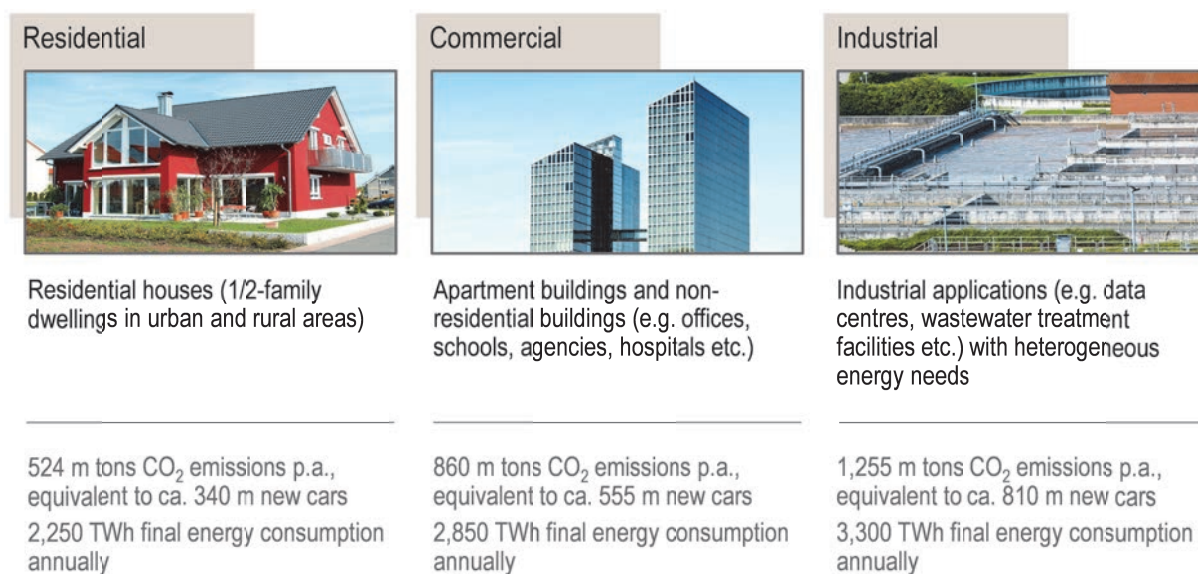


Figure 4: Main market segments for stationary fuel cell applications¹⁰

The residential segment comprises one- and two-family dwellings (1/2-family dwellings). Here the fuel cell has the highest mass-market potential as standardised heating solutions typically target a large variety of buildings, i.e. both new buildings and the building stock with different sizes and degrees of renovation. In the residential segment, the mass deployment of fuel cell mCHPs can realise substantial

¹⁰ Residential emissions reflect share of total residential CO₂ emissions (heat and power) per year. Comparison with new cars assumes 1.55 tons CO₂ per new car and year. Commercial sectors comprise other sectors and share of total residential CO₂ emissions industrial segment comprises manufacturing industries and construction and other energy industry own use. All figures for EU-28.

savings in primary energy, local emissions and energy costs. Stationary fuel cells primarily seek to replace existing gas heating solutions as integrated CHP applications, but could also operate as pure base-load micro power plants in addition to an existing heating solution like a gas condensing boiler.

The commercial segment encompasses both residential (i.e. apartment buildings) and non-residential buildings (i.e. education buildings, health buildings, industrial buildings, storage buildings, office buildings, commercial/retail buildings, agriculture buildings and other buildings). This segment tends to show high standardisation potential, but may ultimately also require customised heating solutions, especially for larger commercial buildings; in many cases, supplying heat is still the primary demand driver for integrated fuel cell CHP applications, but power-driven add-on solutions have potential as well.

The industrial segment includes industrial facilities where fuel cells are usable to generate power or heat or cogenerate both, for example wastewater treatment facilities, chemical production facilities, breweries and data centres. Typically, it is the specific industrial process or business model that creates demand and less the power and heat requirements of the building itself. Therefore, stationary fuel cells have to be tailored to the specific needs of the business in question. However, the need for further standardisation on the supply side does not contradict this observation. A standardised modular approach (with repeating parts) and the development of modular concepts may allow for cost-efficient adaptation to specific needs of different industries.

Figure 6 outlines the market potential for stationary fuel cells in the three segments and four European focus markets, considering the heat market in the case of the residential and commercial segment and the specifically chosen use cases in the industrial segment.

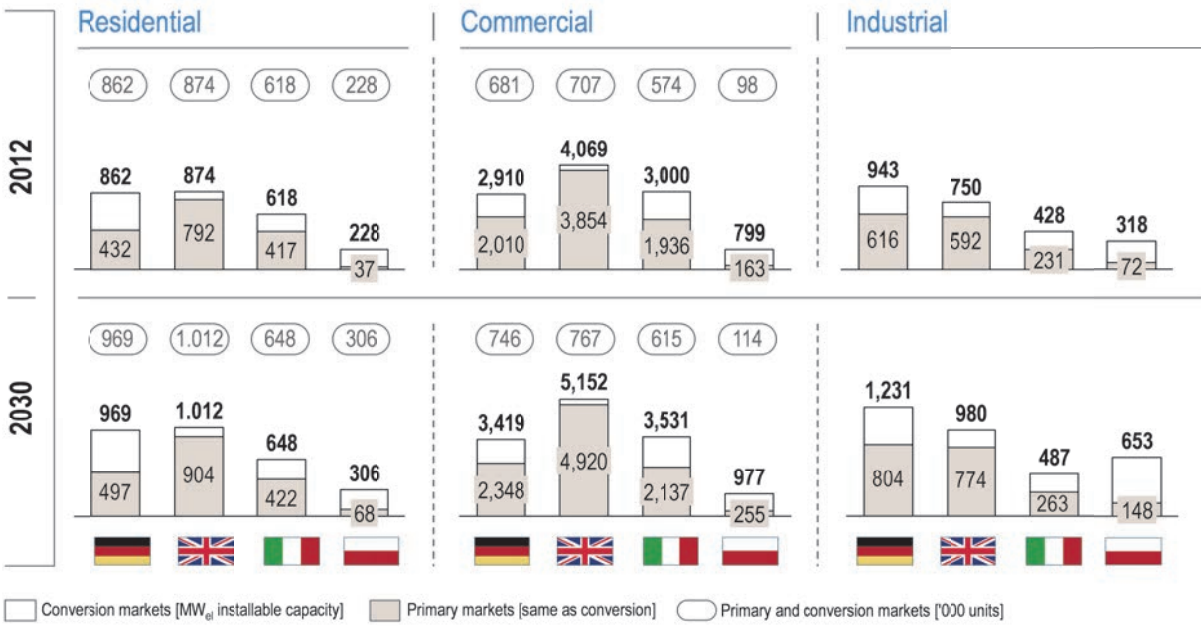


Figure 5: Addressable market for stationary fuel cells across the four European focus markets¹¹

¹¹ Excluding "other buildings" category in the commercial segment; addressable market derived from installed distributed capacities, forecast based on industrial sector expected development in the industrial segment. All capacity-based market volumes that are here presented here (and in subsequent paragraphs) are installable capacities per annum. Primary markets refer to replacements and new installations of gas-heating technologies in the residential and commercial segments as well as existing gas-fuelled distributed generation capacity in the industrial segment. Analogously, conversion markets refer to non-gas technology installations and installed capacity.

Market potential for stationary fuel cells in the residential segment

Heat-driven, integrated CHPs: In principle, the market for integrated, heat-driven fuel cell CHPs in the residential and commercial segment solutions in Europe is equivalent to the market for heated buildings that have access to natural gas. The construction market (new builds and renovations) is the main driver. Ultimately, homeowners face the inevitable decision of choosing a technology that supplies heat to their home. We use a market model based on a two-step approach to identify the annual market potential for fuel cell technologies: conducting an as-is assessment of heating solutions; defining replacement cycles of heating system exchanges/installations necessary given their lifetime.

Power-driven, base-load CHPs: In addition, there is a further market for distributed power generation solutions (with minor consideration for heat) that could generate uptake for stationary fuel cells with high electrical efficiencies and heat as a minor by-product. This market is not driven by exchanges of heating technologies but rather by the availability of a profitable investing case for independent power production – like for the residential installation of solar PV systems. However, market structures are much less established.

1/2-family dwellings make up by far the biggest share in the European building stock in terms of units, accounting for 73% of the total building stock in Germany, 65% in the UK, and 67% in Italy and Poland. Gas is the most prevalent solution in the UK, where approximately 80% of buildings are heated with gas-fuelled technologies. A similar dependency on gas can be found in Italy, where approximately 60% of 1/2-family dwellings use gas as a primary heating solution. In Germany, gas remains the most frequently used primary heating source, but with a share below 50%. In Poland, due to the proliferation of district heating, gas only accounts for 7% of 1/2-family dwellings' heating choice. The addressable market for fuel cell technologies is determined by three main factors: the development of the building stock, driven by the construction of new buildings; heating technology installations in new buildings (including the further expansion of the gas distribution grid); switching of heating technologies in the building stock.

The largest market for stationary fuel cells in the 1/2-family dwellings segment is the UK, where primary and conversion markets amounted to 874,000 units in 2012.¹² Assuming an average size of the fuel cell system of 1 kW_{el}, the total addressable primary market is approximately 900 MW_{el}. In 2030, the market is expected to increase to 904,000 replacements and 904 MW_{el}. The size of the primary market for gas heating solutions in Germany and Italy is very similar, both beyond the 400 MW_{el} mark. Germany's conversion market makes the total market potential nearly equivalent to that of the UK. Poland is the smallest potential primary market with approximately 40 MW_{el} annually, increasing to ca. 70 MW_{el} by 2030. Notably, the market potential generated by newly built 1/2-family dwellings accounts for less than 10% of the total addressable markets in Germany, the UK and Italy. The real mass-market for integrated fuel cell mCHPs is in Europe's residential building stock.

Market potential for stationary fuel cells in the commercial segment

The apartment building sector is the largest in the commercial market segment, accounting for 55% of total building stock across all focus markets. The largest primary markets for stationary fuel cell technologies in apartment buildings remain the UK, Italy and Germany. Poland's gas share in apartment buildings is significantly superior to the gas share in 1/2-family dwellings. In the four focus markets, there is an estimated annual primary market potential of 1.69 GW_{el} installed capacity (derived from existing gas-fuelled heating technologies) and conversion market potential of almost 0.59 GW_{el}. Until 2030, the primary market potential could reach 1.77 GW_{el}, whilst the conversion market may increase to

¹² Primary markets comprise gas heating technologies; conversion markets include coal, wood and oil heating systems as well as heat pumps.

0.62 GW_{el}. It is important to note that apartment buildings may either use decentralised or central heating systems – leading to two different technological requirements. For instance, in the UK decentralised solutions are the most common and thus dominant solution whereas in Germany most apartment buildings are fired by larger central heating units.

The non-residential building structure is dominated by agriculture, commercial, storage and industrial buildings. Buildings with more sophisticated power and heat demand such as health care buildings (which include hospitals), education buildings and office buildings amount to less than 10% of the total non-residential building stock. The segment is highly heterogeneous in terms of the overall power and heat requirements as well as the complexity of the procurement decision process. Moreover, within the non-residential buildings segment, there are building types which, due to their usage, do not require heating (especially agriculture buildings, storage buildings and industrial buildings). In total, the non-residential building segment is accountable for a primary market of approximately 7.5 GW_{el} across the four focus markets. The total primary and conversion market potential may reach 12.5 GW_{el} until 2030.

Overall, the commercial sector bears the largest market potential in terms of installable annual capacity. However it features in essential parts (e.g. apartment or office buildings) considerably more complex customer settings and purchasing decision making processes, e.g. multiple owners in an apartment or office buildings that have to jointly choose a new heating technology. This may be part of the reason why the European stationary fuel cell industry so far targets the segment using systems that are primarily designed for other customers (e.g. targeting large apartments with smaller units for 1/2-family dwellings) and why larger systems between 5 to 400 kW_{el} stand at a very early stage of product development.

Market potential for stationary fuel cells in the industrial segment

In the industrial sector, the evolution of the construction market is of minor relevance. Business characteristics are much more important. Economic performance of distributed generation is crucial in the industrial sector and predominantly the highest-ranked criterion in the decision making process. From a range of some 20 specific industrial applications, this study analyses 5 in greater detail.

Prime power for data centres: It is estimated that approximately 2% of the worldwide energy consumption is used by ICT industries. However, the data centre market structure is mostly fragmented and dominated by very small facilities. In contrast, colocation centres are large data centres which usually comprise more than 3,000 servers, and thus require a power capacity of ca. 1.4 MW_{el} – the focus sub-segment for industrial stationary fuel cells. In total, we estimate a primary market volume for stationary fuel cells of approximately 1.4 GW_{el} across all four focus markets related to colocation centres. Data centre power consumption rises rapidly as the growth of larger facilities continues, especially for data centres offering cloud services and other shared services. Data centres are typically particularly very sensitive to power security, an added benefit of fuel cell systems.

Gas-fuelled CHP in pharmaceutical and chemical production facilities: In terms of installed capacity, approximately 5.8 GW_{el} of distributed power capacities can be identified across the four focus markets. The sector accounts for 30% of total installed distributed power capacities in Germany, 14% in the UK, and 23% in Italy and Poland respectively. The share of CHP in auto-generation across focus markets is above 50%.

Biogas-fuelled CHP in breweries as an example for the food processing industry: We differentiate between 'microbreweries' and 'large' breweries. Due to their small size of up to 1,000 hectolitres per year, in microbreweries energy efficiency is a less critical issue. In total, large breweries could account for more than 250 GW_{el} of distributed power capacities across all four focus markets. Thus, the market potential for fuel cell technologies amounts to 126 MW_{el} in Germany, 57 MW_{el} in the UK, 19 MW_{el} in Italy and 54 MW_{el} in Poland.

Biogas-fuelled CHP in wastewater treatment facilities: Currently, 4 TWh of electricity are produced annually from European wastewater treatment plants of which there are almost 10,000 in Germany, more than 8,000 in the UK, 7,600 in Italy and 3,000 in Poland. However, the share of facilities that have invested in anaerobic digestion infrastructure is insignificant. Taking into account only the wastewater treatment facilities that use anaerobic digestion to produce biogas and estimating an annual biogas production of 800,000 m³ per facility, we forecast a total addressable market of almost 175 MW_{el} in the four focus markets for stationary fuel cells. However, given the low penetration of anaerobic digestion, the addressable market could grow substantially.

Status quo of the stationary fuel cell industry in Europe

The European landscape of stationary fuel cells for distributed generation has grown increasingly rich and diverse in terms of the solutions for different markets, segments and use cases that the industry can provide. Fuel cells can meet both fairly homogeneous customer requirements as in residential buildings, but also deliver modularised, tailored solutions for serving the energy needs of such special industrial applications as breweries or wastewater treatment plants.

Different technologies for different market segments and use cases: Stationary fuel cells have diversified substantially in terms of numerous dimensions, such as the underlying fuel cell technologies or the operating strategies in different use cases, e.g. power- or heat-driven operation of a fuel cell CHP unit. The most fundamental differences that translate into diverging performance and suitability for different use cases stem from different technology lines. Different technology types are made of different materials, require different types of fuel and operate at different temperature levels. They even vary to some extent in essential performance characteristics such as higher efficiencies or longer lifetimes – both in terms of current state of development as well as further potential for technical improvement. However, all should be considered as a means to serve varying use case characteristics and customer requirements. In technical terms, different fuel cells are typically categorised by the type of electrolyte they use. The technologies considered in this study are high-temperature and low-temperature Polymer Electrolyte Membrane Fuel Cells (PEMFC), Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC) and Alkaline Fuel Cells (AFC).

Fuel cell mCHPs for residential buildings: One of the most mature clusters of stationary fuel cells comprises fuel cell mCHP systems in the power range of 0.3 to 1.5 kW_{el} installed capacity to supply heat and electricity to residential 1/2-family dwellings or single flats in apartment buildings. Some products are stand-alone, integrated CHP solutions that are heat-driven, whilst others are add-on, base-load CHP products that are power-driven. Both types are highly standardised products with mass-market orientation. Whilst international markets such as Japan have already made substantial progress in commercialising fuel cell mCHPs, numerous European manufacturers are now gradually bringing their products to the market. By and large, European manufacturers are ready for large-scale diffusion. A few companies already sell products mostly under existing public support programmes (e.g. at the level of the *Bundesländer* in Germany); the rest are participating in ongoing large-scale field tests like Callux in Germany or ene.field in all of Europe. In this segment, the European industry structure has predominantly gathered most value creating activities in the continent with genuinely European products coming into the market. The larger part of European manufacturers focuses on development of European fuel cell stacks (mostly SOFC technologies) – either in-house or from European suppliers and also manufactures the complete integrated heating solution in Europe (with most activities currently in Germany). However, the supply chain increasingly globalises. Another (yet smaller) share of European mCHP players procures complete PEM-based fuel-cell modules from Japanese manufacturers and integrates them into complete systems for European markets. However, the important value creating step of system integration (e.g. with an auxiliary condensing boiler, a heat store and all other peripheral components) is performed in Europe.

Fuel cell CHPs for commercial buildings: Unlike in the case of mCHPs for 1/2-family dwellings, the European fuel cell industry has not yet fully developed a significant number of products in a medium power range of 5 to 400 kW_{el}. Products are still predominantly in the R&D and prototype phase (especially up to 100 kW_{el}), some are in the field test stage, but few are commercially available. The European stationary fuel cell industry targeting the commercial segment is generally less robust than the residential segment. A few European stack developers and system integrators now begin to develop first prototypes in the power range of up to 100 kW_{el}. European system integrators have however begun to install first systems in the field in the power range of up to 400 kW_{el} with systems partially being procured from North America where this product segment has advanced further in recent years. The industry is leaning towards SOFC technologies designed to supply base-load power and heat to commercial buildings. Stack suppliers are in the process of partnering with system integrators, engineering consultants and other market players to offer full-fledged solutions for real estate developers. Overall, the market segment is at a comparatively young stage. Consequently, the foremost priority for stack producers and system developers eyeing stationary fuel cells for commercial buildings in a medium power range is to deliver successful demonstration projects and larger field tests to showcase the readiness of the technology.

Fuel cell prime power and CHP solutions for industrial applications: The readiness of the product offering by the European industry for industrial applications is mixed; some are already bringing products to the market. Particularly internationally there is significant experience with several projects. Globally, the industry has made substantial progress in this power range with successful steps towards commercialisation in North America and East Asia. The segment covers a wide range of customised solutions that are driven by the business of the industrial customer in question; applications range from 400 kW_{el} to several MW_{el}. Consequently, the technology portfolio covers multiple types of fuel cells, e.g. PEMFCs, SOFCs, MCFCs and AFCs. For nearly all use cases considered in this study, some European field tests are ongoing. In the industrial market segment, the European stationary fuel cell industry focuses both on genuinely European system developments as well as the integration and adaptation of internationally successful solutions into the European market context. The larger power ranges for fuel cell CHP and prime power solutions have seen the strongest global progress in North America from where systems have started to come into the European market. In addition, a diverse and robust European supplier, system developer and system integrator base has developed over the past decades with players targeting different specific industrial applications and use cases.

Benchmarking fuel cells against competing distributed generation technologies

The study analyses the technical, environmental and economic performance of distributed generation from stationary fuel cells against competing conventional technologies in more than 45 use cases across the pre-defined markets and customer segments. We look at six different generic fuel cell systems representing the European stationary fuel cell industry as they all show distinct technology characteristics, operate under different strategies, meet specific customer requirements and feature different degrees of market readiness.

Technical performance

The technical performance of stationary fuel cells depends on a range of factors such as the surrounding energy system (e.g. the central electricity generation mix), the use case and customer requirements, the technological characteristics of the fuel cell system, and the resulting operating strategies.

In the residential market segment, the main technical distinction of different fuel cell mCHPs is between fully integrated mCHP solutions as fully-fledged heating systems and add-on CHP solutions for on-site power generation with additional heat production. Fully integrated systems are combined

solutions of a fuel cell mCHP module, an auxiliary condensing boiler and a combined heat and hot water store. The fuel cell mCHP is heat-driven, i.e. follows the heating and hot water consumption demand of the household. Whenever the mCHP supplies heat to the building, it also cogenerates electricity that is either consumed by the household or supplied to the distribution grid depending on the household's electricity demand patterns. The integrated auxiliary condensing boiler meets peak heat demands that cannot be covered by the fuel cell mCHP.

Add-on CHP solutions are installed in addition to an existing heating solution; manufacturers position them as highly efficient distributed power generation units (60%_{el} and more) – with some additional heat production. They are power-driven, i.e. produce base-load electricity by and large all year around irrespective of any specific on-site demand patterns. Electricity is consumed either on site or supplied to the grid. The cogenerated heat is optimised for constant hot water supply. The existing heating solution (e.g. a gas condensing boiler) continues to be the primary heating solution for the building demanded.

As a simplified example, Figure 2 illustrates the technical performance of an integrated, heat-driven mCHP for distributed cogeneration of heat and electricity. As the outcome of different technical performances, the illustration compares the difference in the annual primary energy needs of a household with an integrated fuel cell micro-CHP solution compared to a household supplied exclusively by grid power with a state-of-the-art gas condensing boiler.

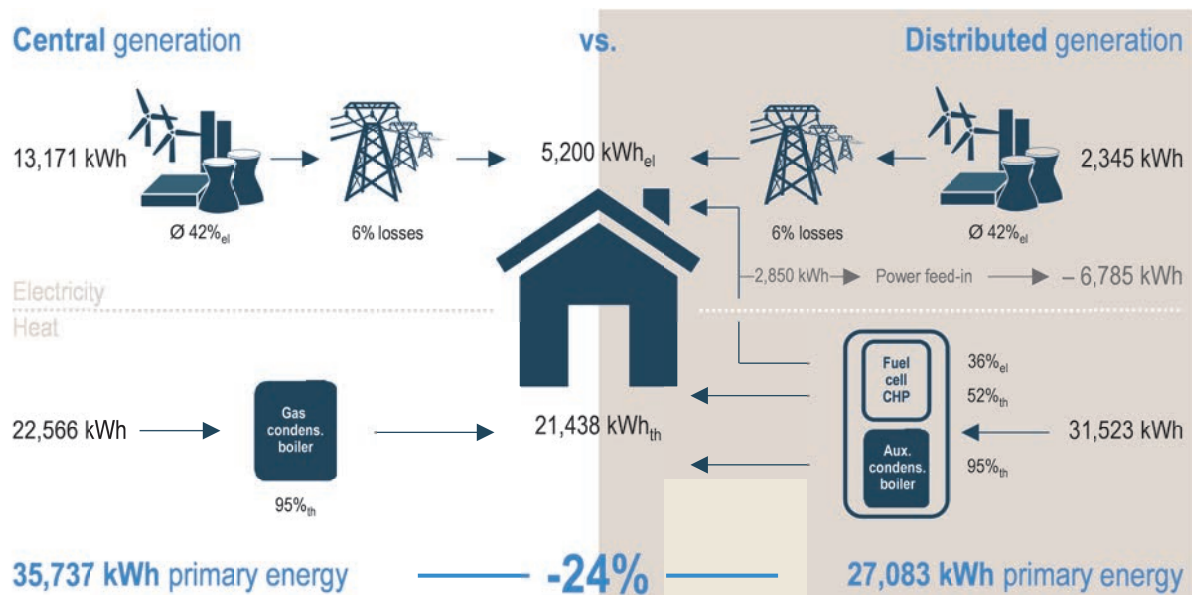


Figure 6: Exemplary, status-quo primary energy consumption of central and distributed generation¹³

Contrary to base-load add-on systems that run largely irrespective of on-site demand patterns, the heat demand patterns of the household directly influence the technical performance of integrated heat-driven mCHP solutions. Specifically, the overall heat demand, peak heat demands and heat demand profiles over the course of the year impact operating hours and output of the heat-driven fuel cell mCHPs. Heat-driven, fuel cell mCHP systems have demonstrated operating hours in a typical range of 6,000 and 8,000 per year in ongoing field tests across Europe. The system configuration like installed capacities,

¹³ Exemplary, current comparison of a German, partially renovated 1/2-family dwelling with four residents considering grid power supply and heating with a state-of-the-art gas condensing boiler on the left and a generic, gas-based fuel cell mCHP with an auxiliary boiler and some residual grid power supply on the right. Primary energy is accounted for according to the total-balance or power-credit methodology considering the average power mix (i.e. power feed-in is credited with the primary-energy equivalent of the electricity substituted in the mix). All efficiencies displayed are average net efficiencies. For further details on assumptions and calculations, please see Chapter E of the Full Report.

electrical and thermal efficiencies and technology flexibility (e.g. modulation capacities, start-stop performances) plays a strong role as well.

In the market segment targeting apartment and commercial buildings, technical performance by fuel cell CHPs in the power range of from 5 kW_{el} to 100 kW_{el} has yet to be demonstrated. Given the structural requirements of heat and power, both heat-driven and base-load power operating strategies are conceivable – as for the residential segment. Efficient performance at partial loads and resulting modulation combined with more flexible opportunities for heat storage can result in long operating hours under heat-driven operating strategies. As add-on base-load electricity producers, emphasis has to be put on optimising on-site consumption vis-à-vis feed-in in order to maximise economic benefits. Beyond 100 kW_{el}, both heat-driven and base-load projects in commercial buildings are ongoing to demonstrate sustained technical performance. Given similar technology characteristics, primary energy savings are estimated to be in the same relative range as for smaller systems for residential segments.

In the industrial segment, the technical performance of stationary fuel cell systems depends on the use-case requirements that have to be met. For prime-power applications like data centres (where heat is not required), stationary fuel cells flexibly follow the on-site power demand or operate in base-load mode at 100% demand, feeding excess electricity into the grid. In other applications, the fuel cell operation and technical performance may depend on the availability of on-site fuel like biogas in wastewater treatment facilities or breweries, but may call for combined heat and power generation as there is an industrial use for both in the production process. Other use cases like chemical or pharmaceutical production process require high and constant power and heat demand on site, calling for a fuel-independent (i.e. natural gas based) cogeneration of heat and electricity – either following a given heat or power demand profile or producing constant loads with feed-in and heat storage. Across all industrial applications, higher electrical and combined efficiencies than competing distributed generation technologies and current central electricity generation mixes lead to significant primary energy savings. As of today, a representative data centre in the four focus markets can annually save between 10% and 30% of primary energy when comparing distributed generation from a 1 MW_{el} state-of-the-art stationary fuel cell system with grid power supply.

Key sensitivities and long term trends influencing technical performance

The currently superior technical performance of stationary fuel cells in terms of primary energy consumption as shown in practice and validated by this study is subject to several key sensitivities. It will vary with different long-term trends in Europe's energy mixes and the energy demand of different use cases (especially the building sector), but the development of fuel cell technology and the composition of natural gas supply will also have an impact.

A decisive trend in the relative primary energy needs of distributed fuel cell generation is the fundamental change in the electricity generation mix. With a growing share of power production from renewable energy sources and decreasing reliance on thermal power plants using fossil fuels, the overall efficiency of centralised power generation will increase (all other things equal). Consequently, grid power supply becomes – *ceteris paribus* – gradually more attractive from a primary-energy consumption perspective than gas-based distributed generation. Over the last decade, the average central power generation efficiency in Germany has increased by 3%, driven by the expansion of renewables and improvements in the efficiency of thermal power plants. As renewables still account for a minority of electricity generation, average grid supply efficiency is also influenced by changes in the residual fossil generation mix. In recent years seen, the residual mix has seen a shift away from comparatively efficient gas power plants to typically less efficient hard coal and lignite thermal power plants, due to various macroeconomic factors. Nevertheless, with clear political targets and a generally strong societal consensus for expanding renewables, gas-based stationary fuel cells in distributed generation will gradually see their primary energy consumption advantages diminish. *Ceteris paribus*, an increase in average efficiency of 1% in the German central power generation mix reduces the primary

energy savings for the household in Figure 6 by 4.7% when choosing an integrated, heat-driven fuel cell mCHP solution over a state-of-the-art condensing boiler. Against this trend, the most significant primary savings of stationary fuel cells can likely materialise in the short and medium term.

A second trend impacting the technical performance and the resulting primary energy consumption concerns the overall energy demand in the key use cases for stationary fuel cells, e.g. the building-related heating applications and also the energy demand in industrial production. In the building sector, the growing political and economic emphasis on energy efficiency will likely trigger more investment in improved building insulation to reduce losses and thereby the overall heat demand. Similarly, industrial production will aim to become more energy efficient, by reducing losses in production processes and making them less energy intensive. Again, the political momentum behind this trend is strong. *Ceteris paribus*, lower overall heat demand due to more energy-efficient use cases influence the technical performance to the detriment of attainable primary energy savings. For example, heat-driven fuel cell CHP systems in the building sector will – *ceteris paribus* – yield fewer operating hours over the year resulting in lower heat output and power generation, given lower heat demand. Moreover, reduced heat demand decreases the absolute primary energy savings attainable.

A third trend may run somewhat counter to the two previous trends mentioned above. As the stationary fuel cell industry aims to further increase (particularly electric) efficiency of their systems, overall technology performance will further improve, e.g. electricity output from heat-driven fuel cell mCHPs. *Ceteris paribus*, an increase in average electrical efficiency of 1% for the generic fuel cell mCHP assumed in Figure 6 increases the primary energy savings for the household in Figure 6 by 5.7% when choosing a fuel cell mCHP over a state-of-the-art condensing boiler. On average, the European OEMs of heat-driven integrated fuel cell mCHPs estimate to increase the electric efficiencies of their systems from now 36% to as much as 42% with growing production volumes and further R&D – as more advanced Japanese manufacturers already demonstrate (please see Chapter D of the Full Report).

Environmental benchmarking

For environmental benchmarking, we examine greenhouse gases (here CO₂), pollutants (here NO_x), particulates and noise and compare which technology solution causes the least annual emissions. Across all markets, segments and use cases, fuel cells can realise substantial local emissions savings for the energy consumer in question. Due to their superior efficiency, the cogeneration of heat and power as well as the comparatively large carbon footprint of the European power mix, stationary fuel cells as heat-driven, integrated CHP solutions can save as much as 40% of household-attributable emissions in German residential buildings compared to condensing boiler systems. When compared to existing low-temperature gas boilers that may be replaced with fuel cells or when additionally considering a switch from oil or coal to natural gas as heating fuel, emission savings are even larger. Additionally, against very carbon-intensive power mixes like the Polish one, fuel cells can realise CO₂ savings for buildings of more than 80%. For power-driven, add-on fuel cell CHPs with electrical efficiencies of 60% and more that run in base-load mode for almost the entire year, CO₂ emissions are even larger. This is due to the longer operating hours and the even larger substitution of grid power supply as well as substantial power feed-in. For all use cases, the emission of pollutants like NO_x can be virtually eliminated by stationary fuel cells. Additionally, fuel cells emit less particulates and noise than their competitors in distributed generation. Figure 7 shows the environmental performance of a fuel cell mCHP vis-à-vis competing technologies. When choosing a new heating technology in a representative, partially renovated 1/2-family dwelling with an annual heat demand of ca. 21,400 kWh located in Munich, Germany, four residents consuming 5,200 kWh of electricity per year could avoid one third in annual CO₂ emissions attributable to their home when choosing an integrated fuel cell mCHP over a

state-of-the-art gas condensing boiler.¹⁴ Attributable emissions of pollutants like SO_x or NO_x could be entirely eliminated. This example takes into account the weather conditions, heat and electricity demand profiles of the described dwelling over the course of a year. The specific results differ when other types of buildings in other regions are used as described in the detailed report. Nevertheless fundamental results remain stable, structurally similar and are thus representative.

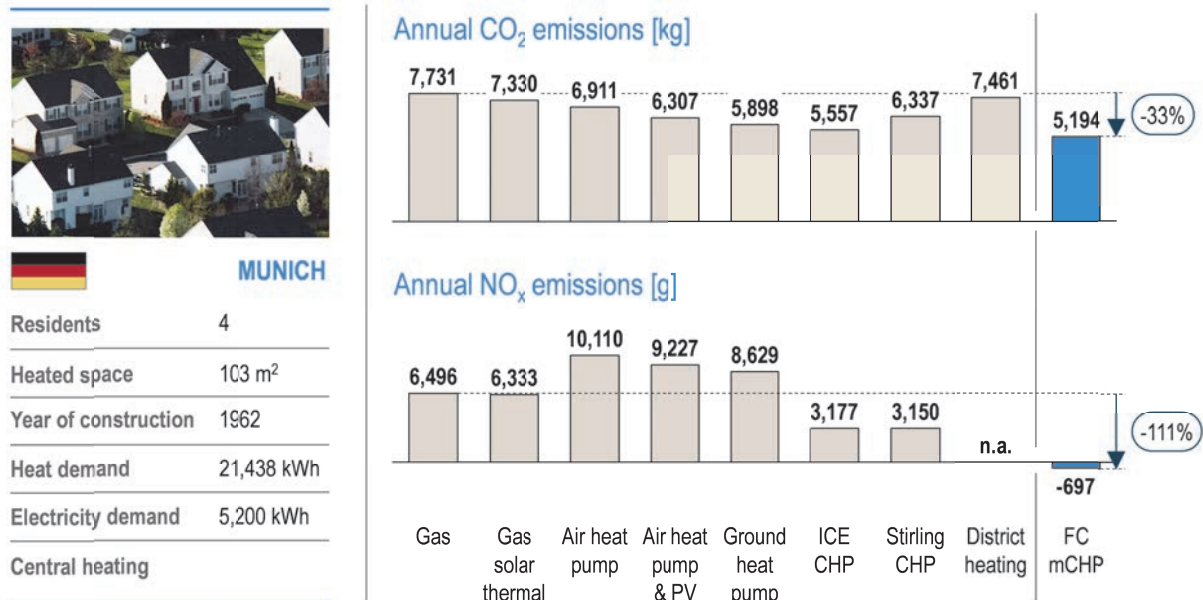


Figure 7: Environmental benchmarking of a fuel cell mCHP in a renovated German 1/2-family dwelling as of 2014

The strong environmental performance is a key advantage of the fuel cell system compared to other heating solutions. It outperforms conventional applications substantially in terms of emissions of greenhouse gases, pollutants, and particulates – even if the conventional technologies are combined with renewable solutions such as solar thermal or PV.

In our analysis, the superior emissions performance of stationary fuel cells becomes evident in every use case – especially when compared to other gas heating solutions. The strongest competition arises from heat pumps as the most efficient electric heaters wherever the power mix providing the heating energy is comparatively carbon-efficient.

The decarbonisation of energy supply as the main sensitivity of environmental performance

The power mix is a crucial determinant of the overall environmental performance of the fuel cell. This is primarily due to the fact that the CO₂ savings attributable to the fuel cell through power generation (whether consumed in-house or supplied to the grid) mitigate the higher carbon footprint from higher gas requirements for heat production. Naturally, the greening of Europe's power mix slowly does away with this advantage. *Ceteris paribus*, the increasing power generation from renewable energy sources like wind, solar or biomass – for which there is a strong political and societal consensus in Europe – reduces the average carbon footprint of the power mix. All other things equal, the ever more decarbonising electricity mix will gradually reduce the emission savings that fuel cell solutions using natural gas as a carbon-efficient, but nevertheless fossil fuel can generate. Competitiveness will first be reduced vis-à-vis efficient electric heating solutions and second vis-à-vis other gas-based heating or distributed generation solutions. The long-term reduction of the emission advantage of gas-based stationary fuel cells has important implications:

¹⁴ For details on the methodology for benchmarking emissions, please refer to Chapter E.

The most substantial CO₂ savings potential is in short- and medium-term, with a decreasing emissions advantage over time: The near to medium term is the crucial time horizon during which stationary fuel cells can realise the most substantial emission savings. This time horizon is shorter in markets with rapidly expanding renewable capacity and a carbon-efficient residual power mix, e.g. with a high share of natural gas CCGT power plants. The time horizon is longer in markets with a very carbon-intense power mix and slower progress of renewables expansion. In any market environment, the industry thus has to swiftly move into the market and quickly generate volume uptake in order to be able to make the most significant difference on emissions, e.g. by tapping the large market potential in the gas-supplied residential and commercial building stock as well as specific industrial applications.¹⁵

The residual conventional generation mix will remain a critical variable over the medium term as it determines the average CO₂ footprint: Nevertheless, the composition of the residual, conventional mix (i.e. the choice between hard coal, lignite, oil or natural gas power plants) will remain a critical determinant for the average and especially the marginal carbon footprint for the coming decades. The increasing CO₂ emissions of the German power mix in recent years despite the growing share of renewables and due to the substitution of gas power plants with hard coal and lignite may be seen as an indicative example of this effect.

Existing infrastructure and grid capacities should be considered in addition to carbon efficiency of fuel supply: When discussing future energy supply, incumbent and incremental network structures have to be considered along with energy sources. Specifically, even an ever greening power mix will likely not necessarily precipitate an all-out substitution of gas-based heating and distributed generation. The substantial existing gas supply infrastructure in large parts of Europe will likely remain an asset that should be utilised – especially when considering the likely implications of increased electric heating that may require significant upgrades of electricity distribution grids.

Possible counter-trends to a decarbonising electricity mix include growing system efficiencies and a decarbonising gas mix: As described above, the European fuel cell industry is confident to substantially increase efficiencies thereby improving the technical performance of their distributed generation systems leading to lower emissions, all other things equal. Furthermore, a decarbonising natural gas supply presents a possible long-term counter-trend to the impact of a decarbonising electricity mix as it would reduce the carbon emissions of all gas-based generation technologies. In the future, the grid-supplied natural gas could for instance show lower carbon footprint due to higher shares of carbon-neutral biogas, higher shares of green hydrogen and input from power-to-gas systems. However, the political will and societal consensus to decarbonise the gas mix currently appears less strong and less concrete as the commitment to expand renewables and decarbonise Europe's electricity supply.

Economic benchmarking

Our main economic benchmarking criterion is the Total Cost of Ownership (TCO) (for example the Total Annual Energy Costs), as decision makers have to make a decision on a technology in order to supply the use case (e.g. a residential building) with energy, i.e. heat and electricity. Taking the view of the decision maker, the benchmarking thus answers question like: How much does it cost to heat a home and supply it with electricity for one year using different technology solutions? Costs include annualised capital cost, maintenance cost, fuel cost and net electricity cost.

Given their high capital cost, stationary fuel cells are currently uncompetitive from a Total Cost of Ownership perspective (i.e. Total Annual Energy Costs in the given benchmarking). However, the OPEX

¹⁵ For further sensitivity analyses of the effect of a decarbonising electricity mix on the emissions performance of gas-based stationary fuel cells, please also see Chapter E.

performance alone is already highly competitive. Consequently, stationary fuel cells can offer a beneficial value proposition to the customer as long as capital cost can be reduced so as to allow for the timely amortisation of the investment. Fuel cell CHP systems yield lower energy costs given their high efficiencies. Regarding maintenance costs, the technology still shows room for improvement if compared to the condensing boiler and the heat pump. However, the maintenance costs are less than 50% of those of CHP systems with internal combustion engines. Industry experts expect further reductions.

Economic performance in residential use cases: Figure 8 shows the economic performance of a generically defined mCHP in a partially renovated 1/2-family dwelling in Germany. The fuel cell system yields the lowest variable energy cost. With sufficient reduction of capital cost, it can offer the most attractive economic value proposition, in terms of Total Cost of Ownership (TCO), as measured by Total Annual Energy Costs.¹⁶

Use-case specific economic benchmarking

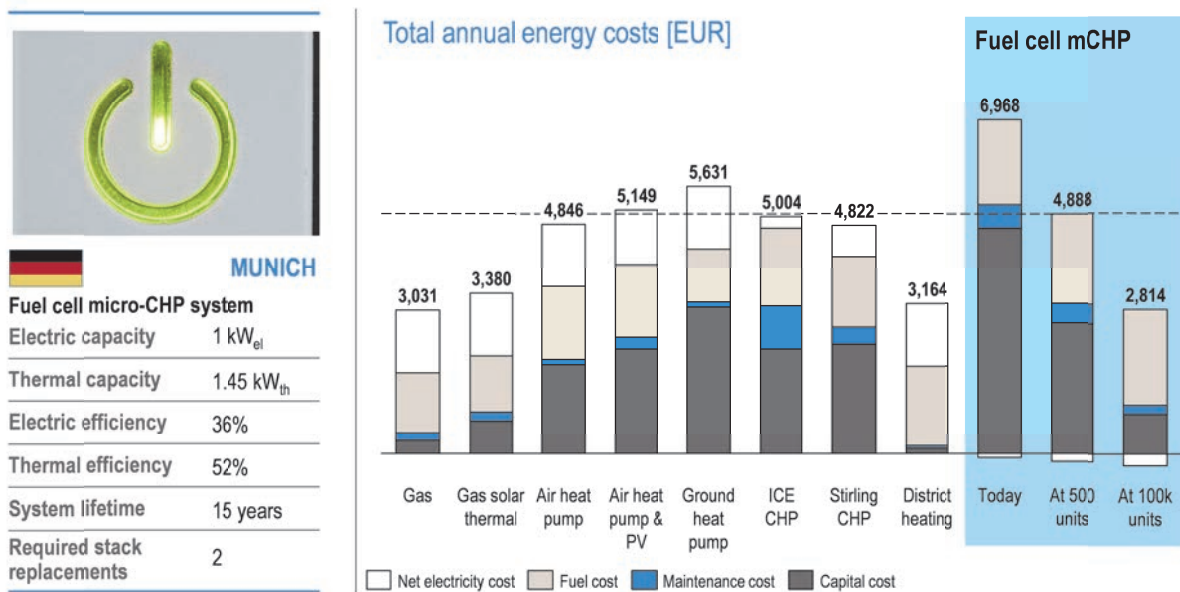


Figure 8: Economic benchmarking of a fuel cell mCHP in a renovated German 1/2-family dwelling¹⁷

The benchmarking results are structurally similar across different residential use cases and markets. Generally speaking, building-related use cases with high heat demand are especially attractive for fuel cell CHPs and CHP solutions in general. This is because long operating hours allow for extensive electricity production, which is either remunerated or saved, given a profitable spark spread. Here, the advantage of longer operating hours of heat-driven CHP solutions in use cases with comparatively higher heat demand (e.g. non-renovated building stock vs. new buildings) translates – ceteris paribus – into a comparatively better economic value proposition. Accordingly, fuel cell CHPs and CHP technologies in general are particularly suitable for application in the building stock with higher heating

¹⁶ For details on the methodology for benchmarking Total Cost of Ownership (TCO), please refer to Chapter E.

¹⁷ Net electricity costs are assessed as the residual, annual cost for electricity purchases that exceed the feed-in from any on-site electricity production, e.g. from solar PV or any CHP technology. Negative electricity costs thus reflect higher earnings from feed-in than purchase from power grid. Fuel costs reflect annual cost of heating fuel, i.e. natural gas for gas-fuelled technologies as well as electricity for heat pumps at the respective household prices. Capital costs reflect an annuity of the initial investment in the respective system and any required re-investments calculated over a uniform time horizon. Cost reductions for the fuel cell mCHP are shown along cumulative production volumes per company.

demand than new buildings. As heating requirements in the residential sector decrease with the implementation of energy efficiency measures such as advanced building insulation, this advantage of CHP decreases. Furthermore, the spark spread is a crucial driver of the fuel cell's economic competitiveness. A high electricity price coupled with a low gas price can reduce OPEX substantially. In this regard, Italy currently provides the most attractive fuel price environment, followed by Germany and the UK. However, sensitivities are delicate. An unfavourable gas price development, combined with modest electricity price increases would disproportionately benefit electric heating. Countries with low electricity prices such as Poland and France are thus currently less attractive for fuel cell CHP solutions.

Economic value proposition in commercial buildings: The commercial segment has great potential for economically beneficial deployment of fuel cell CHP systems. This is true for systems around 5 kW_{el} as well as 50 kW_{el} CHP applications¹⁸ – especially in buildings with high heat demands that allow for long runtime hours, such as apartment buildings in the building stock with central heating infrastructure and warm water supply. As regards the spark spread, the same observations as in the residential sector apply for the commercial and industrial segment – even though some large consumers with a sufficiently large electricity demand may benchmark lower electricity prices against the fuel cell as they have a more favourable bargaining position. Here, distributed generation from fuel cells may face tougher competition. In terms of the energy demand of commercial buildings, high heat-to-power ratios tend to offer best conditions for the economic performance of heat-driven fuel cell CHPs and CHP solutions in general. Consequently, hospitals are particularly interesting use cases, and to a lesser extent office buildings and commercial buildings like retail centres. For a representative, smaller hospital with 200 beds, economic competitiveness with condensing boiler solutions is within reach if current prototype capital costs of a hypothetical SOFC-based, 150 kW_{el} / 120 kW_{th} fuel cell CHP are reduced by 50%. It is, however, important to emphasise that European fuel cell CHP products in the medium power range are currently far from market readiness. At the moment, European stack suppliers and future manufacturers are forming partnerships to provide complete heating solutions and pursue or complete first field tests and demonstration projects.

Competitiveness in the industrial segment: The industrial segment is highly use-case specific and complex. Given the considerable emphasis on costs in this segment, CAPEX reductions are indispensable to advance market penetration. The fuel cell system already possesses a competitive advantage with regard to net energy costs. This may even improve further if further technical efficiency improvements are achieved. However, the positive performance in terms of net energy costs is insufficient to cover the large CAPEX gap of the stationary fuel cell compared to the conventional CHP technologies. Of the industrial CHP cases considered in the economic benchmarking, fuel cells have the strongest competitive position in chemical production facilities, followed by wastewater treatment plants, pharmaceutical production facilities and breweries. In competition with other distributed generation technologies, prime power fuel cells for data centres offer a superior value proposition than engine CHPs given their superior efficiency and limited range of heat applications. Moreover, a further reduction of capital cost of approximately 30% could make fuel cell prime power solutions competitive to the grid across the focus markets Germany, the UK and Italy – even without any policy support. A major benefit of fuel cells in industrial use cases is guaranteed power security which is of particular concern in the context of back-up or even prime power solutions for industries such as ICT, financial services and logistics. In North America, system developers have already started to deliver solutions to such industries. The market for back-up electricity is particularly attractive in countries where grid power supply is frequently interrupted and may stay interrupted for long periods of time.

¹⁸ Commercial applications – as defined here – include systems up to a level of 400 kW_{el}.

Performance levers for stationary fuel cells

In order to jump-start the commercialisation of stationary fuel cells, three performance levers have to be activated as illustrated in Figure 9:

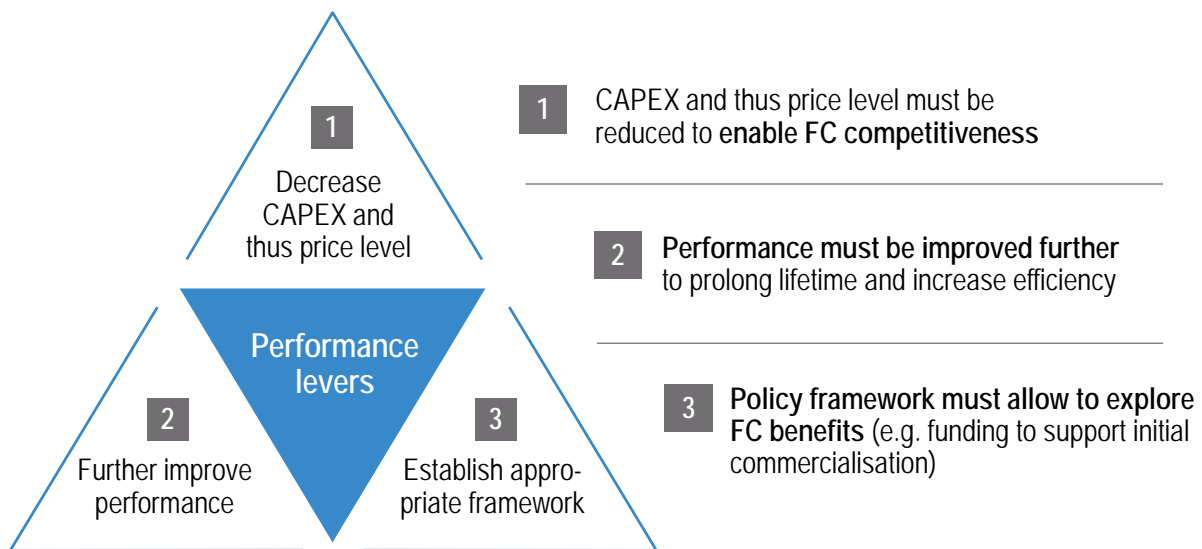
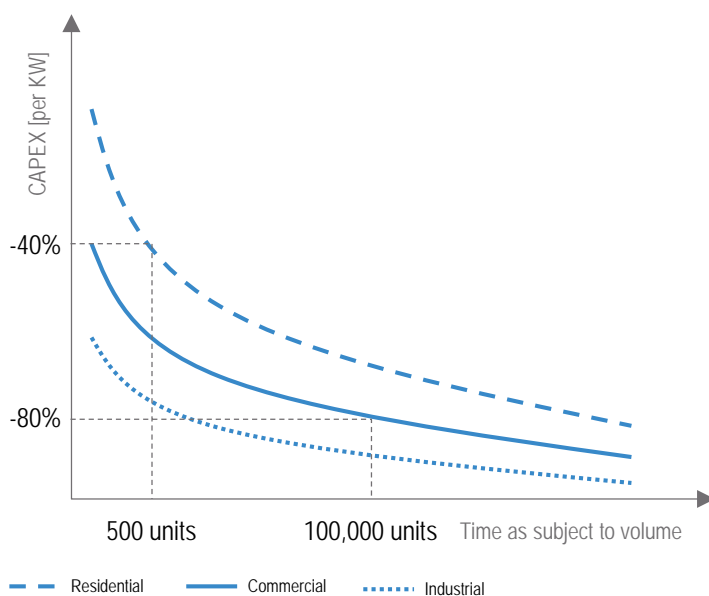


Figure 9: Three main levers to unlock the benefits of stationary fuel cells

Overcoming cost hurdles by reducing CAPEX

Evidently, high CAPEX is currently the greatest impediment to the successful diffusion of stationary fuel cell heating systems, especially for the products that have already demonstrated market readiness in numerous European field tests. To achieve progressive market penetration, substantial capital cost reductions are indispensable.



Main levers to reduce CAPEX

- > Production volume must go up quickly to enter industrialisation stage
- > Many production steps are still manually performed – Learning effects from Japan cannot be adopted
- > Larger volumes allow for automation and bundled sourcing strategies
- > Standardisation must increase also across industries
- > Industry is fully committed to decreasing cost with sufficient installation volumes

Figure 10: Anticipated cost reduction and potential levers with volume uptake and learning effects

The industry data from European manufacturers gathered and analysed in the context of this study suggests that there is significant cost-down potential for all generic fuel cells. For example, manufacturers of fuel cell mCHPs as integrated heat-driven solutions put forth the ambitious estimate that they can reduce cost by as much as 40% when advancing to small series production and reaching the milestone of 500 units of cumulative production per company. This cost reduction already puts a

generic, average fuel cell mCHP system in the price range of high-end heating solutions such as engine CHPs, more expensive heat pumps or hybrid systems with solar PV or solar thermal. In terms of Total Cost of Ownership, fuel cell mCHPs can already outperform such high-end heating solutions at this cost position. Ultimately, the industry believes it can become competitive to today's default heating technology in the residential building stock – the gas condensing boiler.

The mCHP industry expects system costs to drop significantly once companies' production volumes increase to small-series and eventually fully industrialised production. Substantial learning effects are possible. Cost reduction is expected to come both from stack production and added system components.

As regards stack production, the following levers will lower costs per unit: implementing design-to-cost measures; increasing batch sizes to reduce set-up time ratios, direct labour costs and energy use; achieving higher equipment and material utilisation; automation of the production and assembly process especially removing costly and repetitive manual handling through replacement with automatic loading cartridges; reduction in takt time via higher speed lines; larger batch sizes – especially for energy-intensive processes (such as firing for high-temperature SOFCs; eventually completely automatic manufacturing lines with removal of all bar essential manual handling. Moreover, improved and new production methods (such as high-speed metal forming for steel elements) and design-for-manufacturing/design-to-cost processes are expected to drive down stack costs. In terms of added system, cost degression drivers are amongst others: increasing the sourcing of fuel-cell specific BoP components; transitioning suppliers from prototype workshops to larger volume lines; automation and serial tooling of manufacturing with regard to bespoke items, transition from special to standard specification parts, standardisation of component designs and thus gradually growing supplier base, competitive sourcing of components, automated end of line testing for BoP and CHP assemblies.

Further improving the technology and demonstrating market readiness

Apart from growing volumes to yield learning effects and drive down costs per unit, the European stationary fuel cell players emphasise the need to advance the technology as such through further innovation. Particularly critical and equally challenging is the technological progress regarding:

Reducing degradation of the cell, i.e. the gradual reduction in capacity and efficiency, with higher process capacity and narrower variation of cell performance to increase the lifetime of the fuel cell stack (e.g. for fuel cell mCHPs initially beyond 20,000 operating hours, later beyond 40,000 and even 80,000 operating hours – as other fuel cells have already demonstrated) to eventually eliminate stack exchanges over the system design life; increasing the robustness of the stack design that can withstand critical situations (emergency shutdown etc.) to eliminate risk of stack failure through external factors; increasing electrical efficiency to account for increasing electrical demand and decreasing heat demand in the building sector; design-to-cost and design-for-manufacture and assembly both within stack production and in terms of system integration.

The improvement of the technology is particularly critical for all fuel cell producers targeting the commercial segments and most manufacturers with industrial fuel cells as well as some of the mCHP manufacturers that do not have a market-ready product yet. For these companies, the successful delivery of ongoing field tests (e.g. ene.field) and the successful completion of future demonstration projects are of utmost importance to send a clear signal of commitment and ability to deliver to all stakeholders, especially policy makers and market actors.

Routes to commercialisation for stationary fuel cells in Europe

Beyond necessary cost reduction and technology innovation, it is important for the industry to strategically pursue suitable business models for commercialising stationary fuel cells. Business models comprise market-product combinations, the configuration of the value chain, the definition of Go-2-

market approaches as well as the development of revenue models. In order to succeed with the large-scale diffusion of stationary fuel cells in Europe, the industry has to both consider established business models and also innovate new ways of playing the market for distributed generation.

Market-product combinations: To jump-start commercialisation and quickly realise uptake for market-ready products, the industry should primarily target European markets with well-developed gas infrastructure, a favourable policy framework for CHP and generally high awareness the technology. These are chiefly Germany, the BENELUX countries, the UK, Italy, Austria and Switzerland. For heat-driven CHP solutions, the buildings stock offers substantial volume potential, but new buildings may be easier to access as customers face a technology decision anyway. As regards industrial processes, system developers should continue to target power-sensitive industries where the major benefit of power security matters most, e.g. data centres or other ICT applications. At the same time, heat-intensive industries like chemical production are attractive cases for large-scale fuel cell CHPs.

Value chain configuration: Across the European stationary fuel cell industry, the current configuration of the product value chain is similar to the Original Equipment Manufacturer (OEM) or system integrator. Suppliers deliver material and components to stack suppliers who in turn sell fuel cell stacks to system developers that are in charge of assembly and overall system design. Arguably, the structural weakness of the small European supplier base is most critical for the fuel cell value chain today as it is caused by high investment risk due to overall uncertainty and leads to unfavourable sourcing conditions. Here, the supply of ready-made fuel cell modules from Japan to European mCHPs OEMs is a clear exception. In some less mature European segments there are not even dedicated system developers today, but the value chain currently concentrates on stack development alone.

Go-2-market: As regards the Go-2-market from the system developer to the end customer, different segments have more specific characteristics:

Integrated fuel cell mCHPs targeting the heating market: In Western Europe, the mass market for heating solutions in 1/2-family dwellings and apartment buildings is driven by strong established OEMs, wholesalers as well as a highly fragmented, regionalised industry of installers – of which there are more than 45,000 in Germany alone. The installers typically hold the key to the customer today. Product sales (with warranty or service contracts) via the three-step channel tend to be the dominating revenue model, with other influencers like architects playing a role in the decision making process of homeowners. In order to successfully reach large-scale diffusion, fuel cell OEMs will likely have to rely on the existing Go-2-market setting in the heating market. Therefore they should incentivise, educate and seek partnerships with wholesalers and installers to jointly create demand from end customers, e.g. via targeted marketing activities. Beyond the current market setting, potential enablers to circumvent the established sales channels are utilities, especially gas traders and suppliers. Utilities could reap the benefits of secured gas supplies along with the marketing of fuel cells. Furthermore, partnerships with utilities can create opportunities for implementing leasing and contracting models for heating solutions that are currently less prevalent in the residential sector, but may be particularly suitable for innovative, more valuable and expensive products like fuel cells. However, efforts of fuel cell firms to effectively partner with utilities have so far proved challenging, especially with integrated power and gas suppliers.

Base-load, add-on fuel cell mCHPs targeting the electricity market: The market for distributed power generation solutions in Europe like solar PV tends to operate differently than the heating market. Customers are typically more price sensitive and products are typically sold as investment assets aiming at a specific return. Consequently, stationary fuel cells operating mainly as small power plants with little heat supply can play in a much wider field of marketing, but have fewer pre-established structures to work with. The contact with customers occurs via a wide range of actors, such as utilities, energy consultants, installers, or other building-related players. It appears that this market field needs to be developed with more efforts than needed in the heating segment. However, if developed at some point in time the electricity market could bring higher returns.

Commercial fuel cell CHPs in medium power range targeting the heating market: The Go-2-market strategy for the commercial segment may require different organisational processes than the residential segment. One primary element of distinction is the role of planners, engineers and consultants in communicating the benefits, and directly marketing the fuel cell. Planners, engineers and consultants are key influencers in the commercial segment and may exert a strong push effect on the market, in favour of fuel cells as a heating system. Technology providers should therefore seek close partnerships with such players – an activity that stack suppliers and future system developers in Europe are just starting. Upcoming demonstration projects should be used to put such partnerships to work. Installers are expected to be subcontracted, although their role may develop in the future by becoming a first contact centre for end users. Utilities could also play an important role in the Go-2-market strategy, given their current business links to end users via the gas distribution.

Customised B2B solutions for industrial prime power or CHP: For high-investment distributed generation assets for industrial applications, financing requires close attention as the first step of the upstream value chain and a pre-requisite of every Go-2-market. Planners, engineers and consultants play an important role in the value chain configuration. Specialised offices currently cover both planning and sales. System developers in the market also have a direct sales channel, though their primary business is the assembly and installation. Specialised industrial service providers usually perform the regular service of the equipment. The industrial Go-2-market is currently dominated by the system developer. However, this marketing channel is limited in its scope. A successful commercialisation manages to leverage the customer base by including additional players such as planners, engineers, consultants, industrial service providers and utilities in the direct sales channel.

Recommendations to industry members and policy makers

In any case, in order to reap the substantial benefits of stationary fuel cells at different levels, the industry has to undertake significant efforts to bring down cost and improve quality whilst the policy framework has to be supportive. It is paramount to stress the contractual relationship of industrial commitment and policy support – the former is indispensable for justifying the latter. Clearly, the fuel cell industry has to take the lead. Policy commitment and financial support should be subject to specific industry targets for cost reduction and quality improvement that have to be met.

Generally, the industry has to commit to and deliver on specific cost reduction targets; furthermore, it has to sustain and demonstrate high performance. In return, policy makers can commit to CHP and fuel cell distributed generation and support the large-scale diffusion by establishing support mechanisms. Industry targets should be set as target cost/price, target quality, target efficiency/durability, at a specific number of produced units. For example, at company level system cost should be reduced by 40% when 500 mCHP systems per company are brought to the market.

Strategic recommendations: Complete and enhance the business model

With respect to the evident economic, technical, supply chain, market access, acceptance and regulatory hurdles that the stationary fuel cell industry has to overcome, we put forward specific strategic recommendations across all market segments. They are summarised in Figure 11.

	Industry	Policy makers
Economic barriers	<ul style="list-style-type: none"> > Push for achieving cost reduction targets > Pursue new revenue and financing models (esp. contracting and leasing offerings) 	<ul style="list-style-type: none"> > Put in place temporary financial support schemes, such as investment or project-based support > Align relevant existing policy measures
Technical barriers	<ul style="list-style-type: none"> > Deliver on ongoing demo projects and field tests > Tackle main technical challenges (esp. stack durability, overall robustness, efficiency) 	<ul style="list-style-type: none"> > Fund further R&D on critical technical paths > Expand support for demonstration projects and field tests across all segments
Supply chain barriers	<ul style="list-style-type: none"> > Initiate industry collaboration for standard setting > Join forces along the value chain to offer full DG solutions, e.g. with engineering firms 	<ul style="list-style-type: none"> > Demonstrate and communicate commitment to stationary fuel cells > Continue and expand industry dialogue (VC, G2M)
Market access barriers	<ul style="list-style-type: none"> > Seek new partnerships in Go-2-market, e.g. for sales force and service capabilities > Educate existing Go-2-market players 	<ul style="list-style-type: none"> > Maintain current CHP support and prevent erosion via conflicting regulation > Remove obstacles to innovative financing
Acceptance barriers	<ul style="list-style-type: none"> > Raise awareness with end users to create pull effect > Disseminate results of prototyping, demo projects and field testing 	<ul style="list-style-type: none"> > Campaign for benefits of the fuel cell, particularly in terms of emissions and energy savings
Regulatory hurdles	<ul style="list-style-type: none"> > Lobby for tighter regulations on local emissions > Communicate and lobby environmental benefits of fuel cells 	<ul style="list-style-type: none"> > Commit to the decarbonisation of the gas grid > Reform eco-labelling at EU level > Tighten local emissions regulations

Figure 11: Strategic recommendations across segments to overcome barriers to commercialisation

Economics: The benchmarking identified significantly higher capital costs associated with the stationary fuel cell in comparison with competing technologies. In terms of operational expenditure, the fuel cell is already highly competitive today, due to a favourable spark spread in several European markets. The high capital cost is the greatest obstacle to the commercialisation of the fuel cell in Europe. We therefore urge industry members to make capital cost reduction the highest priority on their R&D agenda and to pursue ambitious near-term targets for cost reduction. Fully aware that the economic performance hinges on production volumes, policy makers are encouraged to support the diffusion of stationary fuel cells for CHP financially on a temporary basis, in order to accelerate sales, and deliver on production targets. Furthermore, support schemes and other economic policy measures should be aligned on a European level in an attempt to stimulate the development of standardised stationary systems. For example, consistent, reliable feed-in tariffs could play an important role and complement subsidies. Such tariffs create revenue streams that encourage new business models for Energy Service Companies (ESCOs) and incentivise asset utilisation to the maximum possible. Given their higher overall value propositions as innovative CHP solutions, fuel cell CHPs will likely remain more CAPEX-expensive than conventional technologies like condensing boilers. To overcome this hurdle especially in price-sensitive markets, it is imperative to enable non-cash-sale transactions. Consequently, any regulatory barriers to innovative financing models (e.g. leasing, contracting, Power Purchase Agreements) should be removed to allow fuel cells to commercialise.

Technology innovation: This study identified several shortcomings on the technical side that ought to be addressed. Primarily, stack degradation rates still have considerable room for improvement in many fuel cell clusters as well as electrical efficiency, stack robustness and system lifetime. We recommend that the industry address these issues with the utmost consideration to satisfy the performance expectations of future customers and prioritise these areas on their R&D agenda. It is paramount that product quality is demonstrated before pursuing large-scale diffusion. Some fuel cell clusters like mCHPs have already made substantial progress, now other segments need to follow suit. Policy makers are encouraged to make financial support for R&D available. We encourage industrial stakeholders to seek out opportunities for demonstration projects, and policy makers to support them financially.

Production methods: Furthermore, we recommend players on the brink of full-scale commercialisation to pursue lean production methods with a higher degree of automation. Primarily, it is important to reduce scrap rates by automating key production steps such as printing, cleaning and stacking. These

steps lead to an increase in batch sizes, whereby set-up times and the direct labour costs can be reduced. Stack sintering was identified as a potential bottleneck in the production process of SOFC stacks, due to its long duration and energy intensity. We recommend intensifying efforts to resolve this problem. Improvement of the production should also include efficient and effective quality management.

Supply chain: The configuration of the value chain revealed that suppliers of materials and components as well as stack suppliers often only perform single highly specialised steps in the value chain. Standardising the production of stacks and reducing the dependency on single suppliers and the risk of unforeseen supplier exits represents an important step in the successful commercialisation of the fuel cell. Furthermore, we encourage manufacturers to vertically integrate additional value-add steps in order to secure the supply chain. The latter could also be achieved by creating and maintain strategic partnerships with downstream suppliers. Policy makers are encouraged to continue and expand the facilitation of an inclusive industry dialogue. Furthermore, a clear commitment to the fuel cell technology by policy makers increases investment security and thereby supports the industry's access to financing.

Market access: In terms of market access barriers, the study identifies path dependency for conventional heating solutions in consumer decisions and a general lack of awareness of the fuel cell as potential obstacles to commercialisation. OEMs should seek cooperation and partnerships with planning, engineering and consulting offices. Thereby, it is possible to consolidate and leverage the customer base and offer comprehensive CHP solutions. Furthermore, particularly in the residential segment, installers have an important local footprint and are key players at the customer base. On the one hand this means that accessibility may be somewhat restricted due to existing business relationships, reinforcing the path dependency outlined above. On the other hand, collaboration with installers can prove to be a highly promising business model for both sides, which is why we recommend partnerships in this area. The potential for alternative Go-2-market partnerships, such as with utilities, should also be extensively explored. In order to increase the general awareness of the stationary fuel cell technology, we encourage stakeholders to educate Go-2-market partners extensively and rally their support in communicating the technology benefits to the customer. We encourage policy makers to campaign in support of favourable market conditions, emphasising the benefits of combined heat and power production and the favourable environmental performance of the fuel cell.

Acceptance: Acceptance barriers stem from the lack of credible and convincing information to the customer. Therefore, it is important to communicate the success stories of demonstration projects clearly and extensively and perform projects in locations with high visibility, particularly in the commercial sector. Marketing campaigns may prove valuable to those players active in the residential segment, in order to create a pull effect for the fuel cell. Policy makers can play an important role in lowering acceptance barriers by displaying public commitment to the technology.

Regulatory framework: With regard to regulatory hurdles, the stationary fuel cell industry in Europe requires a reliable regulatory framework that is supportive of (distributed) CHP technologies and that places emissions savings as well as reduced primary energy consumption at the heart of energy legislation. In this regard, immediate need for action concerns – for example – the introduction of a compulsory EU Energy Label for heating technologies which duly considers primary energy savings of micro-CHP units through a proper methodology that is reflective of the performance of the product in terms of primary energy consumption. Moreover, we encourage the industry to lobby for tighter restrictions on urban emissions, given the preferable emissions balance of the fuel cell in terms of CO₂, but also concerning pollutants and particulates. This point is highly relevant to policy makers, especially on a regional level. Given that fuel cells will likely be gas-based in the short to medium term diffusion, a long-term environmental strategy should embrace the decarbonisation of the gas grid. We encourage policy makers to include this approach on their agenda and to promote sustainable biogas production from renewable sources. At the same time, industry players need to ensure their system's compatibility with a greener gas mix that includes larger shares of biogas, hydrogen as well as synthetic natural gas.

Segment-specific recommendations for policy support

As a first, volume-focused public funding framework, we propose a segment-specific subsidy scheme that is limited in time and scope. It should be seen as the start of a European market introduction program whose continuation should be subject to close monitoring of industry performance.

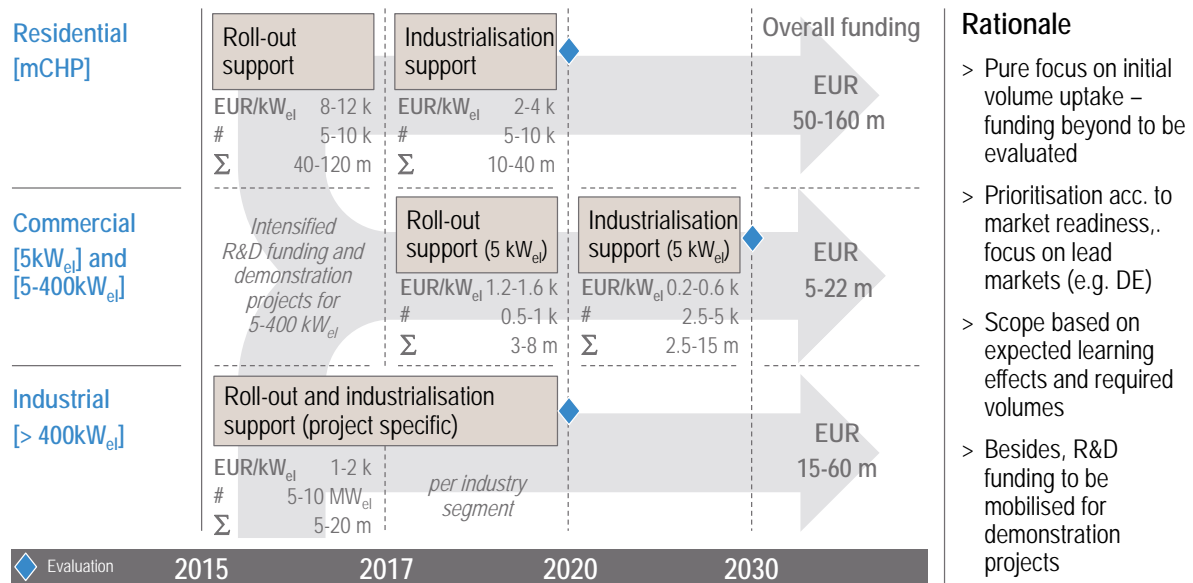


Figure 12: Potential funding framework for segment-specific policy support for commercialisation¹⁹

Recommendations concerning fuel cells targeting the residential segment

In order to reap the substantial benefits in terms of higher energy efficiency, lower emissions and accelerated distributed generation, fuel cell system providers and stack suppliers that are already on the brink of commercialisation need public support in the roll-out phase – as a targeted measure to build a bridge towards market introduction. Provided that the industry successfully delivers on ongoing demonstration projects, such support schemes should be implemented – however clearly limited in time and scope. Policy makers should closely monitor performance and cost improvements. We recommend 8,000-12,000 EUR/kW_{el} support for units deployed in the residential segment. Support should be made available for the deployment of 5,000 to 10,000 units in this segment, amounting to total funding of 40 to 120 m EUR. During this phase, the stationary fuel cell could become economically competitive with high-end technologies on the basis of Total Cost of Ownership, i.e. heat pumps and engine-based CHP technologies. After the roll-out phase, we recommend making further funds available depending on the achievement of pre-defined cost targets that are to be regularly monitored by the corresponding policy authorities. In order to support industrialisation in this segment (which industry experts project to commence in 2017) support of 2,000-4,000 EUR/kW_{el} for 5,000- 10,000 units would be needed. The overall financial requirements for the residential segment amount to 50-160 m EUR. During the industrialisation phase, stationary fuel cells for the residential segment may achieve significant cost reductions and establish themselves amongst competing solutions – laying the foundation for deployment at mass-market scale. Given the decreasing emissions savings attributable to the fuel cell as Europe's power mix decarbonises²⁰, we encourage the funding to be made available to the industry following this temporary funding scheme and as soon as possible.

Recommendations concerning fuel cells targeting the commercial segment

¹⁹ Industrial segment: Assuming three focus industries selected to reach volumes for achieving learning curve effects

²⁰ For more information please refer to the benchmarking analysis in Chapter E.

The commercial segment has high potential as a market for stationary fuel cells.²¹ However, considerable policy support is needed in order to spur the development of viable concepts for commercialisation, i.e. further R&D. We recommend policy makers to make funds available for additional demonstration projects in order to support the industry in developing prototypes, proving the technology in-field and disclosing the progress to commercial decision makers. However, before funds can be granted the commercial segment must significantly learn from the other segments to reach a viable starting point. At this point in time, the only conceivable subsidy framework aiming at volume-uptake for systems in the commercial segment includes the niche of 5 kW_{el} CHP systems for centrally heated apartment buildings; larger CHP systems between 5 and 400 kW_{el} have yet to demonstrate market-readiness. To the contrary, 5-kW_{el} systems take part in e.g. the ene.field project, even though suppliers are not ready to deliver products to the extent that mCHP OEMs already can. The roll-out phase for the commercial segment is thus assumed to follow the roll-out of the residential segment with 5 kW_{el} taking the lead. We expect the industry to have greater commercial success by benefiting from spill-over effects from the residential segment, specifically, lower costs from suppliers and a higher degree of stack standardisation. Overall, we encourage policy makers to consider committing 1,200-1,600 EUR/kW_{el} support during any future roll-out phase funding 500-1,000 units of 5 kW_{el} CHP systems. During this phase, stationary fuel cells in the commercial segment have the opportunity to become economically competitive with heat pumps, establishing themselves amongst high-end heating technologies. Conditional on the achievement of pre-defined cost targets, funding could further be made available for 5 kW_{el} CHP systems in a second phase. This support should specifically be dedicated to achieving industrialisation, with 200-600 EUR per kW_{el} support for 2,500 to 5,000 units. Given the promising results of the environmental and economic benchmarking exercises in larger commercial use cases (office building, shopping centre, hospital), we encourage funding authorities to intensify funding of demonstration projects to validate the technical and economic viability of 5-400 kW_{el} CHP fuel cells in such use cases – comparable to the Topic FCH-02.5-2014 " Innovative fuel cell systems at intermediate power range for distributed combined heat and power generation" under the current FCH JU Call for Proposals.

Recommendations concerning fuel cells targeting the industrial segment

There are several good experiences with stationary fuel cells for power generation in the industrial segment. The benefits of the technology are outlined extensively in the benchmarking chapter. In terms of recommendations, we believe that players within the industrial segment should require additional references in the European market in order to promote the technology image in the market for auto-generation. We encourage policy makers to make funding available for projects involving appliances greater than 400 kW_{el} and to commit 1,000 to 2,000 EUR per kW_{el} in policy support. Funding should focus on specific industry applications, because consistency in the type of application reduces complexity and improves learning potential due to the comparability of results. Funding should thereby be sufficient to help existing players with marketable products to reach learning curve effects. The first main step is thereby reached at around 5 to 10 MW_{el} cumulative production volume per company. Focus industries should be selected according to a proper evaluation. Funds shall be committed accordingly, e.g. if three focus industries are selected an equivalent of 15 to 30 MW_{el} cumulative installations should be funded. The number of funded installations should match the number of players in a way that learning curve steps can be reached. However, if learning curve effects cannot be realised – despite sufficient volumes– funding should be stopped in the respective industry. In order to make the benefits of the fuel cell CHP visible to industrial decision makers, it is important for fuel cell representatives and policy makers to choose projects with high visibility and communicate benefits clearly and exhaustively.

²¹ The following recommendations are applicable to commercial buildings requiring systems greater than 5 kW_{el}.

Furthermore, the industry should lay particular emphasis on means of automating production processes and improving stack robustness and durability on the back-end side. Regarding policy commitment, we support the introduction and extension of CHP production premiums. Past experiences, particularly in Germany, have shown that CHP premiums are a purposeful and goal-oriented means of encouraging the deployment of efficient CHP technology. Moreover, this policy measure is highly visible to industrial customers and signals political support. We regard the industrial segment to be very noteworthy on a European level; however, there is still great room for improvement in the production process, value chain configuration and go-to-market strategy.

The recommendations are solely concerned with commercialisation and do not take into account that some fields need other support measures, e.g. the commercial segment will need to engage in further research and development to develop systems in the range of 5 to 400 kW_{el} that could actually serve the given market needs. Moreover, the recommendations are drawn under the assumption that other factors remain rather stable. Assuming that the actions are taken we believe that two possible pathways of development are viable. Either the fuel cell positions itself as high-end niche market technology with specific characteristics and advantages or it positions itself as a mass-market technology outperforming today's standard solutions. The potential development pathways are described below.

Market outlook: The commercialisation of stationary fuel cells in Europe

The market development of fuel cell systems depends on a variety of factors such as cost degression achievements, policy support, and the evolution of the energy mix. Although the fuel cell bears many advantages over other technologies, we believe that its commercialisation can only succeed by achieving competitive price levels. However, if the market proves unable to deliver sufficient price reductions, stationary fuel cells will continue to struggle to become self-sufficient. Then, further support programmes should end accordingly and the market will hardly develop further. Contrarily, if cost degression targets are reached, the market has significant potential. In this line of thought we see two potential pathways – one where fuel cells become a comparatively high-end technology such as engine-based mCHPs or certain heat pumps in the residential market today and another where fuel cells even become a mass-market solution and substitute today's standard applications such as condensing boilers. In the first pathway, stationary fuel cells may achieve a sustainable market share of 4-20% in the long run depending on the segment and relevant competitive technologies. The high pathway may even lead to a situation where the fuel cell could take leadership in gas-based technologies and reach market shares of up to 20% to 60%, respectively. Given the proposed funding schemes, residential and commercial markets must carry the responsibility to deliver high-quality and cost-efficient systems. Other market segments will pick up afterwards and will bear significant potential to diversify and internationalise. However, if cost targets are reached, the all-out commercialisation of fuel cells in Europe is still subject to many open questions. Some are answered by this study, others need to be answered by the actions of fuel cell industry and other key market players. For example, the successful commercialisation will continuously depend on the policy frameworks in place, e.g. to what extent it remains favourable to distributed (co-)generation. Therefore, market development remains in part ambiguous and subject to the concrete steps taken by industry players as well as policy makers.

PART II:

Full Report

A. Introduction, methodology and general study approach

Objective of this study: An in-depth assessment of the potential for commercialisation

The energy systems across Europe face significant challenges. As Europe's energy systems are changing, there are numerous challenges EU member countries have in common: growing challenges for grid stabilisation, triggered by a surge in variable feed-in from renewable energy sources, new balancing concepts required to cope with variability, significant investments required to modernise the electricity grid infrastructure. Stationary fuel cells for decentralised heat and power production can offer important contributions to the successful resolution of these challenges. This study provides a comprehensive and structured account of the current and future market potential for fuel cells, building on market analysis, the detailed development of scenarios and a benchmarking analysis with competing technologies. Based on this detailed assessment, and the identification of current barriers to commercialisation, we are able to make recommendations for the commercialisation of stationary fuel cells to industry members and policy makers.

Scope and overall context of the study: The technologies considered

This study deals with the European industry of stationary fuel cells on its path to industrialisation and commercialisation. It covers the European industry at large. Typically, different fuel cells are categorised by the type of electrolyte they use. The technologies considered in this study are high-temperature and low-temperature Polymer Electrolyte Membrane Fuel Cells (PEMFC), Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC) and Alkaline Fuel Cells (AFC).

Sponsor of the study: The Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

This study has been sponsored by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a public-private partnership between the European Commission, the fuel cell and hydrogen industry and a number of research bodies. The FCH JU supports research, technological development and demonstration activities in the field of fuel cell and hydrogen energy technologies in Europe.

General study approach: Interactive approach including industry and public-sector stakeholders in the EU

The study builds on an interactive approach involving stakeholders who play a key role in the roll-out of fuel cell distributed generation in the European Union. Each step of the analysis was performed in close collaboration with industry experts. This is particularly true for the development of the scenarios discussed in the text, the technology benchmarking and the joint development of feasible business models.

Participants in the study: A coalition of more than 30 members

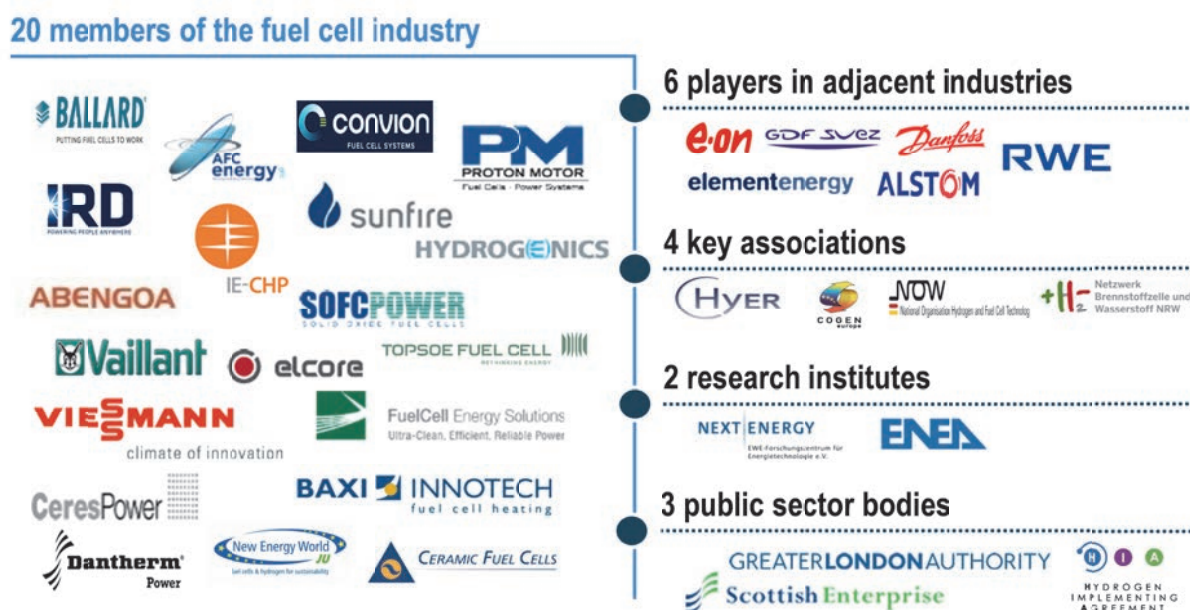


Figure 13: Coalition members and general set-up of the study

The coalition, whose collaboration in providing valuable data, opinions and regular feedback is at the heart of this study, is summarised above. This paper was developed in close collaboration with industry representatives from a broad range of value chain steps, as well as political stakeholders.

Structure of the study: Nine chapters

This study consists of 9 chapters labelled A to I. This chapter provides a general introduction to the content of this paper. The second chapter develops policy scenarios which provide a framework for the analysis. Chapter C identifies the addressable market for fuel cell CHPs. Chapter D presents generic fuel cell systems, which were developed on the basis of input from the industry, and benchmarked against competing technologies in the subsequent Chapter E. Chapter F describes routes to market for stationary fuel cells. The subsequent chapter explores potential barriers to commercialisation. Chapter H provides an overview of policies surrounding CHP in general and fuel cells in particular in several countries. The last chapter formulates recommendations for policy makers and industry representatives, on the basis of the analysis outlined in the course of this study.

Focus markets: Identification of the most attractive geographic markets in the EU for fuel cell distributed generation

Whilst this study aims to draft a Europe-wide strategy for the commercialisation of stationary fuel cells, it also has the ambition to go beyond a superficial EU-level assessment and perform a deep-dive analysis at the level of individual countries and markets. For this reason, this study concentrates on "focus markets" in order to allow for an exhaustive analysis at country level, as well as identifying specific conditions and success factors for commercialisation. The scope of this paper embraces four European countries that have been selected as focus markets.

In order to choose our focus markets, we defined two overarching criteria to guide the selection process: the focus markets should be attractive for fuel cell technologies and they should be representative for different European country clusters. The relative attractiveness for fuel cell technologies is defined by three fundamental criteria: magnitude of the spark spread, size of the overall market and share of high-

polluting fuels in the national energy mix. In order to ensure differentiation amongst the focus markets, criteria such as: climate conditions, GDP per capita, access to natural gas, energy policy framework, efficiency requirements, customer behaviour, etc. have been defined and used for a benchmarking at the European level. As a result of the market selection process, we concentrate our analysis on four focus markets, namely Germany, the UK, Italy and Poland.

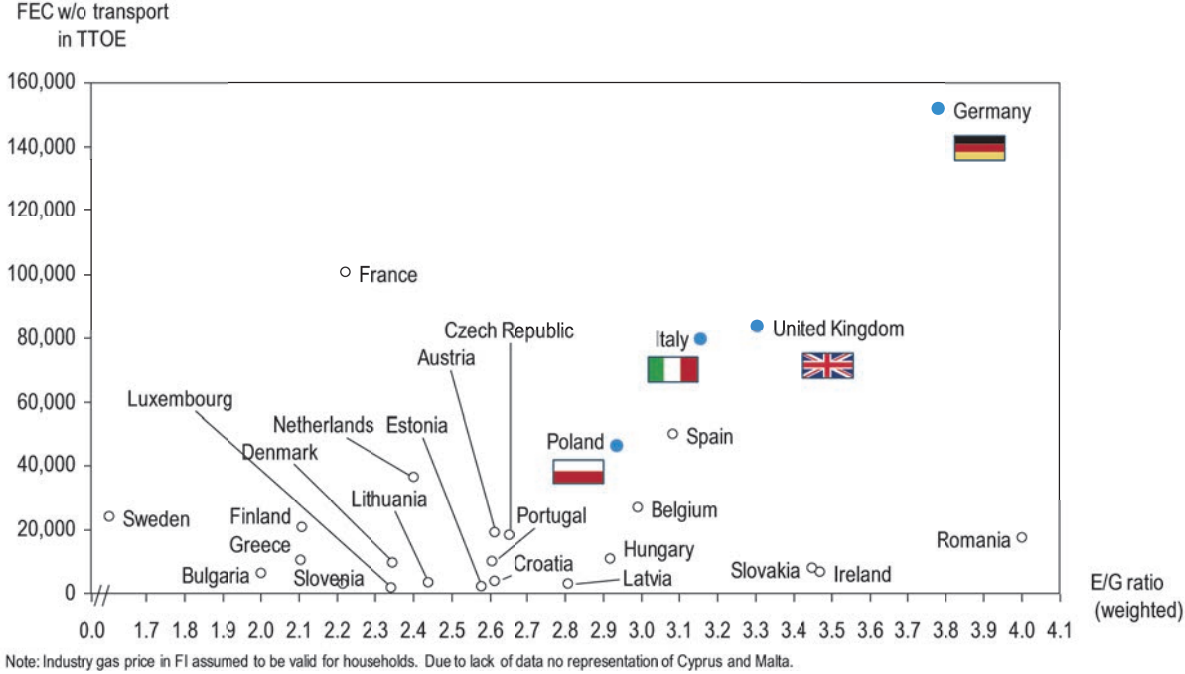


Figure 14: Excerpt from analysis for the selection of focus markets for detailed analysis

Germany has the highest energy consumption in Europe. The spark spread is very high, which makes the market attractive for CHP applications. The absolute consumption of fossil fuels for power production is the highest amongst the EU 28.

The United Kingdom's energy consumption is also high and features a large share of fossil sources and a high spark spread. End customers in the residential sector are particularly price sensitive. The market is characterised by fast diffusion of novel technologies whenever short term savings can be realised. The UK was chosen over France due to the significant amount of energy derived from fossil sources (France is heavily reliant on nuclear energy).

Italy accounts for a relatively high energy consumption, whereby a great share is derived from fossil sources (i.e. coal and petrol). The spark spread is close to the European average. Italy was selected over Spain due to the maturity of the property market.

Poland's energy consumption is close to the European average though energy is predominantly derived from fossil sources (i.e. approximately 90% of current energy mix is based on coal). Poland has an average spark spread and was chosen over Romania due to larger energy consumption and a greater amount of fossil-generated power. Poland is representative for countries with lower income levels and purchasing power, a CO₂ emissions intensive power mix as well as a high share of old heating devices.

Key learnings from Chapter A

- The study outlines a pathway for commercialisation of stationary fuel cells in Europe
- The content was developed in close collaboration with the European stationary fuel cell industry, namely a coalition of more than 30 stakeholders
- The analysis concentrates on four focus markets: Germany, the United Kingdom, Italy and Poland
- We only consider PEM, SOFC, MCFC and AFC in the context of this study

B. Macroeconomic scenarios and development pathways

Scenario development is a tried and tested approach for exploring possible future settings connected to a topic or set of topics in light of extensive uncertainty. However, scenarios – including the scenarios in this study – are not predictive and do not serve to describe a definite future or development. With our scenarios we formulate three future settings, which serve as a backdrop for the further analysis of the future market potential for fuel cell distributed energy generation.

The European Commission has set ambitious greenhouse gas (GHG) emissions reduction targets for the year 2050. The goal is to reduce its GHG emissions by 80-95% compared to 1990 levels.²² The EU energy landscape is the decisive factor in realising these ambitious goals. Lower – and potentially "zero" – emissions energy generation technologies like renewables (e.g. solar, wind) as well as carbon-efficient technologies like fuel cells hold great potential for further GHG emissions reduction in Europe (and globally). In this context distributed generation must be a core consideration, as it encompasses most of the low(er) carbon energy generation solutions.²³ The decisions shaping the energy landscape in Europe in 2050 are being made today. Hence the time period we are exploring stretches from today to 2050.

Methodology: Developing the three scenarios

The three scenarios were developed jointly with a designated group of topical experts from industry, government and civil society organisations within and outside the coalition. As a first step, an original set of relevant influencing factors²⁴ were ranked by the coalition members according to the level of influence they have on the future distributed energy generation market and their level of uncertainty. As a result, 18 high-impact factors were defined. These jointly selected, high-impact factors were then grouped into topical clusters, which represent the pillars along which the scenarios were developed. The policy landscape, i.e. the level of commitment to greener energy and ensuing actions such as increased support for distributed generation, was applied as an overarching influencing factor.

²² Cf. European Commission (2014)

²³ For the purposes of this study, we define distributed energy generation with regard to heat as all modes of energy generation for heat except district heating. For electricity generation, we regard the generation that is connected to the distribution system (high/medium/low voltage), of a scale of < 60 MW_{el} and occurring "on site" (i.e. close to the consumer and potentially part of a virtual power plant) as distributed energy generation. Cf. European Parliament (2010) and European Commission (2003)

²⁴ Original list developed by Roland Berger Strategy Consultants, customised for this study in cooperation with the Study Coalition

Survey based on 54 influencing factors regarding the future of DEG

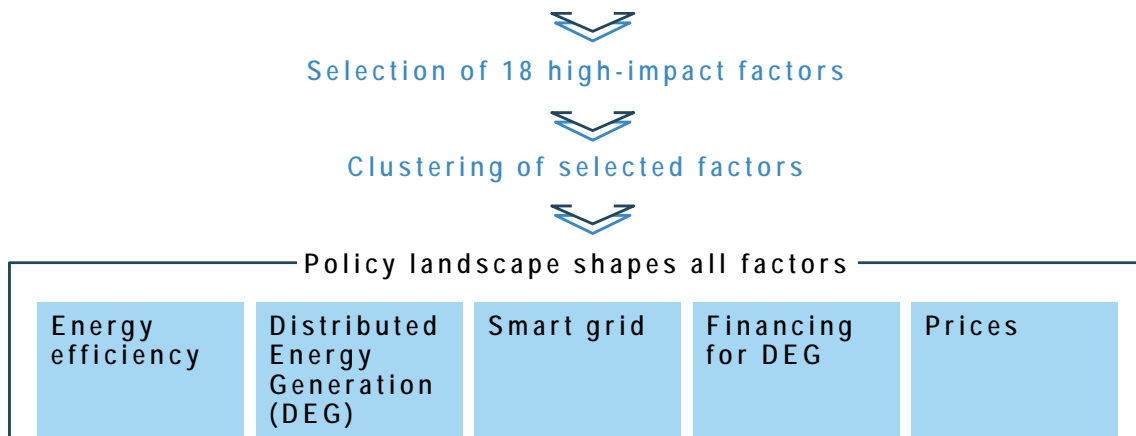


Figure 15: Selection and clustering of important factors for developing energy scenarios

It is important to note that the scenarios are formulated on an EU level, whilst taking into consideration the focus markets (Germany, Italy, Poland and UK²⁵) selected for this study. The variation of the factors in the three scenarios provides the basis for thorough sensitivity analysis regarding the future market potential for distributed generation – fuel cell powered distributed generation in particular. Two of the most decisive inputs in this context are: Firstly, the prices and spark spread for electricity and natural gas – the bigger the spark spread, the higher the incentive to pursue gas-powered distributed generation solutions. Secondly, the price of carbon, which depending on its level succeeds or fails to incentivise switching to low(er) carbon energy generation solutions.

The three scenarios developed in this study

The European Union has firmly stated its commitment to a greener energy future. At the core of this greener energy future is the ongoing expansion of the share of renewables in the energy mix. Many of these renewables (e.g. solar) fall into the category of distributed generation. Hence a higher share of renewables concurrently means a higher share of distributed generation. Fuel cell solutions are part of distributed generation, but not necessarily part of the renewables segment. Nonetheless, fuel cell solutions can make a significant contribution to the aspired-to greener energy future due to their high level of efficiency – in particular when applied for combined heat and power (CHP) generation – and their ability to substitute conventional, carbon-intense technologies, such as boilers. In the longer term, fuel cell technology solutions could even emerge as entirely "clean" solutions by utilising hydrogen rather than natural gas as fuel.

Building on this premise, the scenarios enable us to view three possible 2050 settings within which distributed generation, including fuel cell powered distributed generation solutions, will be established to varying degrees according to how strongly the policy commitment to a greener energy mix has developed.

The three scenarios are

- **Scenario #1 – "Untapped Potential"** with a low degree of distributed generation

²⁵ For more information on this selection, please refer to Chapter A

- Scenario #2 – "Patchy Progress" with a moderate degree of distributed generation²⁶
- Scenario #3 – "Distributed Systems" with a high degree of distributed generation

Policy targets in the EU today: An outlook for the EU

European governments, consumers and the energy industry itself are facing the challenge of defining how to best cope with the substantial changes taking place regarding the environmental, commercial, regulatory and technological regimes that shape the European energy landscape.²⁷ The EU has set course towards its goal of realising a decarbonised, highly economically competitive (e.g. through increased liberalisation) and energy secure Europe. However, effective policy approaches to implement the declared goal of a greener energy future for Europe – one of which must be a clear commitment to distributed generation – remain fragmented. Whilst some countries, for example Germany, are "ahead of schedule" regarding the level of penetration of renewables others are struggling to successfully pursue renewable distributed generation. Fuel cell powered distributed generation presents a particular case in this context, as in spite of noteworthy initiatives like the FCH JU it still struggles to gain critical mass through larger scale commercialisation. In terms of public awareness and support – a powerful driver in and of itself – renewables are by far the better known part of distributed generation compared to fuel cell powered solutions. Whilst recent polls show overwhelming support for renewables²⁸ amongst Europeans, fuel cell technologies and the distributed generation solutions they enable remain far more opaque.

Of all the objectives set out by the EU on its path to a decarbonised, competitive and energy secure future – defined in the short term by the 2020 goals – energy efficiency is proving to be the most difficult to realise. One factor to consider in this context is the untapped potential with regard to the efficiency possibilities of non-renewable energy sources, which suffers – amongst other reasons – from a suboptimal level of combined heat and power (CHP) utilisation. Perhaps the greatest potential for increased energy efficiency, however, lies in the building sector, both residential and industrial. Legislation is increasingly addressing this issue, but there is a long way to go. European Energy Commissioner Günther Öttinger summarised the status quo succinctly when he stated that "*the need for more energy efficiency is glaring*".²⁹ As fuel cell powered distributed generation in particular exhibits comparatively higher energy efficiency than conventional sources at present, it deserves central consideration in this context.

A decisive and currently fairly underdeveloped piece of the puzzle is the smart grid development in Europe. Especially the increasing share of renewables and the coinciding increasing complexity of energy balancing show the need for a smarter grid. The hurdles to realising a smarter grid, however, are far from insignificant, e.g. the massive cost.³⁰ In general, cost and financing are a core concern regarding the realisation of a higher share of distributed generation and a more wide-spread commercialisation of fuel cell powered distributed generation. Though there are public support schemes in place, e.g. by the German KfW bank, the declared goal must be to reach a higher degree of economic

²⁶ Scenario #2 - "Patchy Progress" serves as the reference scenario here and as the general reference scenario for the remainder of the study

²⁷ Cf. European Commission (2014a)

²⁸ Cf. European Commission (2014b): Special Eurobarometer 409 – Climate Change

²⁹ Cf. European Commission (2011), European Commission (2012), IEA (2008); IEA (2013)

³⁰ Cf. European Commission (2011a)

competitiveness to attract private investments. In this context pilot programmes such as "Callux"³¹ in Germany can be decisive, if they prove successful and their success is marketed effectively.

The most relevant energy prices today with regard to fuel cell powered distributed generation are the electricity and natural gas price and the resulting spark spread as a rough margin indicator for energy production.³² The price of carbon is another relevant measure. On an EU level the electricity prices for household and industrial consumers range between 20 and 14.9 EUR ct per kWh, whilst the natural gas prices for household and industrial consumers range ca. from 6.6 to 5 EUR ct per kWh. The implied spark spread, assuming an efficiency factor of 49.1% for gas, as is standard in topical literature, then ranges from 6.6 to 4.8 EUR ct per kWh on EU average.³³ On a country basis and depending on the specific use case the spark spread may lie at a much higher figure, however. The current carbon price is far below intended levels at less than 5 EUR/t. Initial recovery efforts, mainly recent ETS reform measures meant to restore carbon price levels that succeed in deterring emissions, are being implemented and further ones, including options for broader application of the ETS to include a higher share of industry, are planned.

The above depicts the status quo of the distributed generation landscape in Europe. However, it is our goal to look ahead at what the future holds for distributed generation in general and fuel cell powered distributed generation in particular. In the following three scenarios we first take a closer look at possible trajectories for the policy framework and energy market environment and then at how these factors influence the relevant prices (electricity, natural gas, carbon) that in turn shape the market potential for fuel cell powered distributed generation.

Looking ahead: Three scenarios for 2050

The following three scenarios were developed against the backdrop of the current situation described above and based on varying assumptions for the selected high-impact factors shaping the future of distributed energy generation.

Scenario #1 – "Untapped Potential": Describes a 2050 where policy commitment to distributed generation – both renewables and non-renewable yet carbon-efficient distributed generation like fuel cells alike – is lacking. Energy efficiency potential has not been realised, fossil fuels still make up most of the energy mix and European smart grid ambitions remain unimplemented. The price of carbon has failed to recover and the spark spread for electricity and gas prices is low or even negative.

Scenario #2 – "Patchy Progress": Describes a 2050 where there is moderate, yet regionally fragmented policy support for distributed generation. The share of distributed generation from renewables has increased leading to an urgent but as-yet unmet need for a pan-European smart grid for enhanced energy balancing. Energy efficiency has increased, yet further potential remains. The price of carbon has somewhat recovered and the spark spread is moderate.

Scenario #3 – "Distributed Systems": Describes a 2050 where the policy commitment to distributed generation is high, as distributed generation has emerged as the energy generation source of choice. This is reflected in a very high share of renewables in the energy mix and specific policy schemes to push fuel cell powered distributed generation. The high share of renewables is seamlessly integrated into the energy mix thanks to a highly developed, pan-European and interconnected smart grid, which

³¹ Cf. Callux (2014)

³² For the purposes of this study we apply an efficiency factor of 49.1% for natural gas.

³³ Eurostat (2014)

also supports high levels of energy efficiency. The price of carbon is sufficiently high to incentivise the utilisation of low(er) carbon energy generation solutions as well as investments in energy efficiency. The spark spread is high.




Scenarios 2050			
	 Untapped potential	 Patchy progress	 Clean systems
Policy landscape	No commitment to DEG	Moderate commitment – regionally fragmented	High level of commitment to DEG (preferred choice)
Energy efficiency	Remains low – high energy demand	Moderate (increasing)	Well developed (high)
DEG: Renewables	Low – high share of fossil fuels (switch from coal to gas)	Increasing – challenge of energy balancing	High share of renewables
Smart grid	Development is lacking	Regionally fragmented	Advanced, pan-European and interconnected
Spark spread: Electricity to gas	Low	Moderate	High
Price: CO₂ (carrying the cost)	Low (select industries)	Moderate (all industries)	High (all industries and households)
	Small fuel cell market	Growing fuel cell market	Fuel cell mass market

Figure 16: Overview of the three energy scenarios for 2050 ³⁴

Scenario #1: "Untapped Potential"³⁵

Policy support for distributed generation is low, as aspirations for Europe's greener energy future fell short. The main reason for this low level of support is the lack of alignment by Member States along the strategic vision for energy 2050 formulated by the EU in the early years of the century. EU policy support for renewable distributed generation has diminished steadily over the decades, as national interests, e.g. political concerns over the backlash from increasing electricity prices, gained more and more influence and hampered pan-European goals. As a result, policy support for distributed generation is not firm and concrete enough (e.g. no binding renewables targets were implemented after 2020) and it is not sufficiently focused on the full spectrum of distributed generation. Hence, the share of renewables in the energy mix is below potential and public awareness of the full spectrum of distributed generation solutions, including fuel cell powered ones, is low. This in turn means that the broader commercialisation and increased sales of fuel cell powered distributed generation have not materialised and the availability of finance and levels of investment suffered whilst competing technologies were able to compete successfully via comparatively lower prices.

³⁴ Cf. European Union (2011), European Commission (2013), IEA (2013), IEA (2013a)

³⁵ The relevant information regarding the topical cluster "prices" for all three scenarios is included in the following sub-chapter "The Impact on Prices"

Energy efficiency has remained the Achilles' heel of Europe's aspirations regarding the harmonisation of decarbonisation and economic competitiveness. After missing the 2020 goal of 20% efficiency gains, no comprehensive approach was formulated to set a new course and realise the significant untapped potential of energy efficiency. As fossil fuels make up a major share of the energy mix in this scenario (higher than in the other two scenarios) the fact that efficiency gains via increased CHP utilisation were not pursued weighs particularly heavily. Perhaps the largest missed opportunity in terms of energy efficiency, however, occurred in the building sector. Initial advances, e.g. the stipulation that all new buildings in the EU must have "nearly zero-energy" consumption,³⁶ were not built upon by new policy measures and hence resulting efficiency gains were suboptimal.

Despite Europe's ambitious smart grid aspirations only a low degree of penetration was achieved. Lack of a firm and streamlined policy commitment to a pan-European smart grid and the resulting lack of common standards, for example, were the key drivers of this negative development. In absence of a clear policy commitment to the smart grid as key enabler of Europe's energy future, the resulting uncertainty has also deterred much-needed investments to manage the immense cost. In its current state the grid is not able to accommodate well the share of renewables, which albeit lower than in the other scenarios still demands additional efforts with regard to energy balancing.

Financial public support for distributed generation is available on an EU and national level, but decreased subsidies were not sufficiently compensated by non-monetary policy support (e.g. expedited permitting processes for new technologies) and whilst even mature distributed generation technologies struggle with the transition to competing in the market, fuel cell powered distributed generation solutions, which were not able to achieve sufficient levels of maturity, are disproportionately affected. Once promising pilot projects, e.g. ene.field, were not continued after initial trials and their impact was not sufficient to shift public awareness to the full spectrum of distributed generation solutions.

Scenario #2: "Patchy Progress"

Policy support for distributed generation exists, but it is regionally and locally (e.g. city level) fragmented in absence of a systematic and unified support scheme across Europe. Fuel cell powered distributed generation remains one of the more uncommon and lesser known low carbon energy generation solutions, strongly due to a lack of application of pull policy concepts, which could effectively mobilise consumer-driven demand. In absence of a binding 2050 target for GHG emissions reduction (including urban pollution and emissions), only partial recovery of CO₂ prices and the fact that some distributed generation solutions fared less well than others once subsidy levels were reduced have prevented the full realisation of distributed generation potential.

Though Europe increased its efforts regarding **energy efficiency** significantly – the failure to realise the 20% efficiency gains set out in the 2020 goals³⁷ marked a decisive turning point – further **room for improvement remains**. In particular, combined heat and power (CHP) generation, based both on fossil and non-fossil fuels, has not been optimally pursued. On the upside, significant advances have been made regarding the energy performance of buildings, both residential and industrial. The gradual move

³⁶ Cf. European Commission (2010)

³⁷ Cf. IEA (2013)

towards near-zero emissions buildings, especially from 2020 onward, fuelled by EU-wide legislation³⁸ and regional "above and beyond" standards, were successful.

At the same time, the **smart grid development remains fragmented**, since a comprehensive approach to financing the massive undertaking never materialised and merely regional champions continue to lead the way whilst pan-European coverage and interconnectedness are far from achieved. The **fragmented nature of the smart grid also applies to smart cities**. A high correlation is observable between regional and local concentrations of distributed generation and the implementation of smart city initiatives (some of which, e.g. the "Green500"³⁹ initiative in London and its successor initiatives, have been in place for decades), which similarly aim to support decarbonisation, systems optimisation (e.g. energy) and economic competitiveness through streamlined, ICT-powered solutions on the basis of multi-stakeholder partnerships.⁴⁰

Following the select, gradual reduction of subsidies for distributed generation a **stronger emphasis has been placed on the non-monetary aspects of policy support**, e.g. a more efficient regulatory and administrative system within which processes connected with a higher share of distributed generation in general, and fuel cell powered distributed generation in particular, can take place faster and achieve better outcomes.⁴¹ **A significant part of distributed generation financing models remain dependent on public support**, but a continuous trend towards public-private pilot projects and their successful implementation has mobilised **increasing private investments as well** – occurring on a public, commercial as well as private level.

Scenario #3: "Distributed Systems"

In line with a comprehensive commitment to a green energy future for Europe, a decisive and unified policy shift towards support and promotion of distributed generation, including fuel cell powered distributed generation, has taken place. distributed generation has become the energy generation solution of choice. Prioritised EU and Member State level policy support for distributed generation is driven to a large extent by its positive contribution to efficiency gains. Policy support for the whole spectrum of distributed generation is provided in both monetary (e.g. R&D support) and non-monetary form (e.g. optimised permitting procedures⁴²). The high share of renewables (the highest amongst the scenarios) is largely due to the increased economic success and competitiveness of distributed generation. Through emphasis on pull policy concepts, e.g. feed-in tariffs for distributed generation-generated electricity, a higher level of public interest was successfully mobilised for the full spectrum of distributed generation, including for example a push for distributed generation in rural areas to decrease the level of grid dependency.

Energy efficiency has emerged as the "fuel" of the EU's decarbonisation goals. This is enabled by clear and binding regulation and targets and a fundamental shift in consumer behaviour, e.g. increased awareness of climate change. Regarding the efficiency of non-renewable fuels a highly increased rate of CHP was the decisive factor for the achieved improvements. Great advances in terms of efficiency have

³⁸ Cf. European Commission (2013)

³⁹ The London Green500 initiative provides energy efficiency advice and support

⁴⁰ Definition of smart city concept based on European Parliament (2014)

⁴¹ Cf. European Commission (2011a)

⁴² Cf. European Commission (2011a)

also been realised in the building sector. Strict implementation of EU standards is the case, with several countries even surpassing these. In Germany, for example, highest standards in both new build and renovation are the norm. Regulations like the EneV 2009 have been consistently developed further as advances in technology and building techniques enlarged the scope of what is possible. The systems view that was adopted with regard to building efficiency includes the utilisation of carbon efficient solutions for heating.

Smart grid penetration has reached pan-European, interconnected levels. This is mostly thanks to a firm policy commitment and the emergence of energy balancing as a business model through capacity markets. Hence, large energy providers are incentivised to act as aggregators and medium voltage network managers. Smart grids are viewed as the key enablers of Europe's energy future, through market coupling and highly improved integration of RES.⁴³ Firm policy commitment in turn generates higher investments, both public and private, and availability of financing. Gas-powered storage options have become a key enabler of load balancing – the role of hydrogen in this context has also increased steadily.

Financing for distributed generation has increased and broadened its scope to more equitably cover the full spectrum of distributed generation solutions. The availability of financing from private sources has significantly increased, driven by successful pilot projects and the firm policy commitment to more carbon-efficient energy generation solutions.

The impact on prices: The role of the spark spread

The spark spread of electricity to gas serves as an indicator for fuel cell attractiveness. Concurrently, it indicates the level of attractiveness of producing power from natural gas. However, it is crucial to note that this power efficiency only depicts one part of the overall efficiency potential of fuel cell solutions and the resulting economics. In fact, a significant part of the positive environmental and financial impact the application of fuel cell powered distributed generation can have stems from its use for heat generation in CHP solutions. In the latter case, the efficiency rate has the potential to reach more than 90%.

It is important to note that the scenarios do not aim to predict future energy prices. Instead, possible ranges of energy prices are illustrated, concurrently resulting in possible spark spreads for the three different scenarios and enabling a better understanding of the market potential for fuel cell powered distributed generation. The scenarios and the information within them should be understood as analytical, not predictive.

Looking back at the past ten years,⁴⁴ the spark spread has increased on an EU level, for household consumers by approx. 2.6% and for industrial consumers by approx. 3.6%.⁴⁵ Regarding carbon, the current picture in Europe is one where the ETS system has not recovered from the massive oversupply of certificates due to the financial and economic crisis. At the time of writing the CO₂ price is below 5 EUR per ton. This price level fails to significantly incentivise a switch from high to low carbon energy generation solutions – distributed generation being the latter. Looking ahead, however, the carbon price is likely to recover from this current slump.

⁴³ Cf. European Commission (2013)

⁴⁴ Cf. Eurostat (2014)

⁴⁵ The ten year increase is indicated as Compound Annual Growth Rate (CAGR)

In the three scenarios the spark spread – resulting from the electricity and gas price development – and the price of carbon move within certain ranges: low, moderate and high. In the following we provide a brief overview of the most relevant prices per scenario.

Scenario #1 – "Untapped Potential"⁴⁶: Describes a 2050 where the **spark spread is low**. This is observable for both household as well as industrial consumers in 2025 already and becomes even more evident by 2050 when the spark spread has turned negative. This is due to the relatively stronger gas price increase (compared to the trajectory of the electricity price) in absence of decisive policy support to push gas rather than other fossil fuels. Here the 2050 prices for electricity range from 24.5 to 18.2 EUR ct per kWh for household and industrial consumers respectively. For gas the forecasted price range stretches from 18.8 to 16.7 EUR ct per kWh for household and industrial consumers respectively. At the same time, the **price of carbon in the EU is still low at < 16 EUR/t**, largely due to lacking success of the ETS reform. One reason for this is the failed enlargement of ETS-coverage, meaning that it is still only select industries which the ETS applies to. Though this price range represents up to tripling of the current price of <5 EUR/t it fails to properly incentivise a switch to low carbon or carbon-efficient energy generation solutions. The low price on carbon goes hand in hand with the high share of fossil fuels that is one of the defining features of the Untapped Potential scenario.

Scenario #2 – "Patchy Progress"⁴⁷: Describes a 2050 where the **spark spread is at a moderate level** for both household and industrial consumers. Following historical trends, the evolutionary development of the electricity and gas price leads to a noticeably bigger spark spread than in the "Untapped Potential" scenario, with gas prices rising at a lower rate than electricity prices. Here the 2050 prices for electricity are the same as in the Untapped Potential scenario and range from 24.5 to 18.2 EUR ct per kWh for household and industrial consumers respectively. For gas the forecasted price range stretches from 7.5 to 5.7 EUR ct per kWh for household and industrial consumers respectively. The **price of carbon has recovered significantly in this scenario and measures approx. 16-33 EUR per ton**. Further price recovery, however, is hampered by the persistent lack of a global agreement and price coordination.⁴⁸ In Europe, ETS reform has led to an expansion of its coverage across all industries.

Scenario #3 – "Distributed Systems"⁴⁹: Describes a 2050 where the **spark spread is at a high level** for both household and industrial consumers respectively. The spark spread is significantly higher than in the reference scenario (see above) and in comparison to today's levels it has ca. doubled by 2025 already. By 2050 the effect is even stronger, due to the relatively higher increase in electricity prices in light of the massive cost of smart grid development, whilst gas prices are relatively low, as demand has dropped in light of higher shares of renewables. Here the 2050 prices for electricity range from 50.8 to 37.8 EUR ct per kWh for household and industrial consumers respectively. For gas the forecasted prices are the same as in the reference scenario at 7.5 to 5.7 EUR ct per kWh for household and

⁴⁶ The model that was utilised to quantify the spread of the electricity and gas prices for the "Untapped Potential" scenario is based on EUROSTAT data, a modified version of the high electricity and gas prices scenario from European Commission (2014a), where the growth rate of the gas price was increased in alignment with the "Untapped Potential" storyline (see detailed scenario description above) and Roland Berger Analysis

⁴⁷ The model that was utilised for the "Patchy Progress" Scenario forecast is based on Eurostat (2014), the High Electricity and Gas Prices Scenario from European Commission (2014a) and Roland Berger Analysis

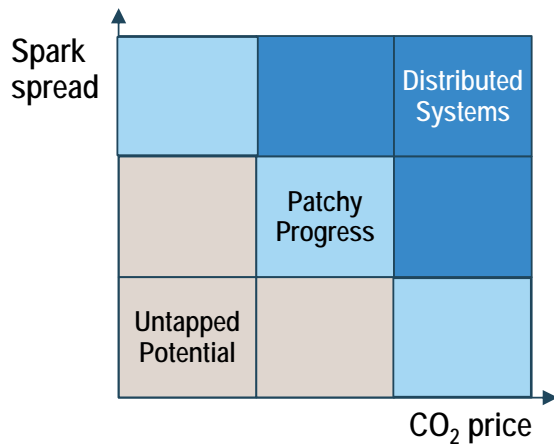
⁴⁸ Based on the "Jazz" scenario, in World Energy Council (2013); the "Jazz" scenario shares core similarities with the Patchy Progress scenario, e.g. the fragmented rather than internationally aligned carbon pricing

⁴⁹ The model that was utilised to quantify the spread of the electricity and gas prices for the "Distributed Systems" scenario is based on EUROSTAT data, a modified version of the high electricity and gas prices scenario from European Commission (2014a), where the growth rate of the electricity price was increased in alignment with the "Distributed Systems" storyline (see detailed scenario description above) and Roland Berger Analysis

industrial consumers respectively. **At 55-60 EUR/t the price of carbon has recovered decisively in this scenario.**⁵⁰ Some 2050 estimates even see the price of carbon exceeding 100 EUR per ton.⁵¹ ETS reform and an increasingly globalised approach to carbon pricing were the main drivers. The coverage of the ETS includes household consumers as well. The high price for carbon is in line with the high electricity price in this scenario and supports both the EU's energy efficiency and carbon emissions reduction goals.

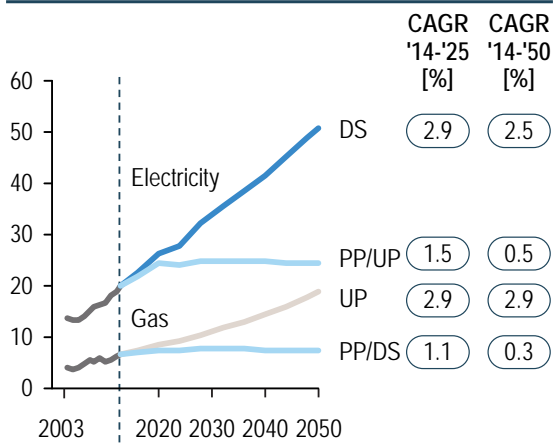
⁵⁰ Based on the "Symphony" scenario in World Energy Council (2013); the "Symphony" scenario shares core similarities with the Distributed Systems scenario, e.g. the high level of renewable energy

⁵¹ Cf. Ernst & Young (2012), citing the UK government

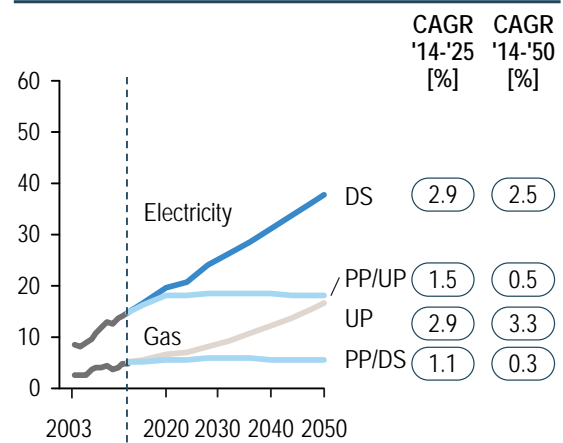


	E-price	Gas price	Spark spread
Distributed Systems	high	low	high
Patchy Progress	moderate	moderate	moderate
Untapped Potential	low	high	low

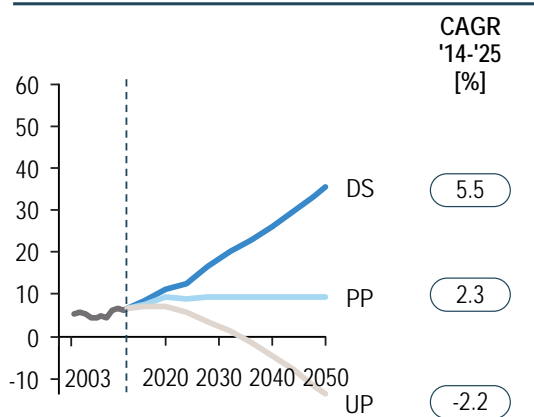
Price development Household – Electricity, natural gas [EU; 2003-2050]



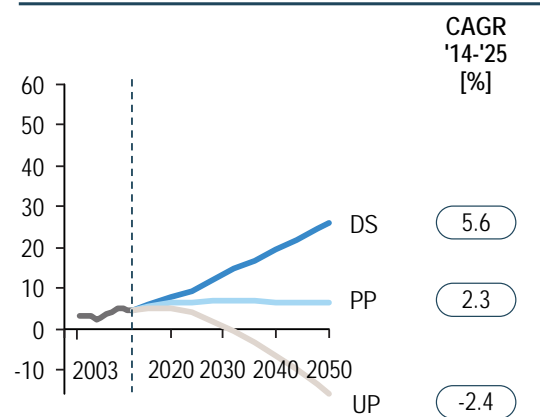
Price development Industrial – Electricity, natural gas [EU; 2003-2050]



Spark spread development – Household [EU; 2003-2050]



Spark spread development – Industrial [EU; 2003-2050]



DS: Distributed Systems PP: Patchy Progress UP: Untapped Potential

Figure 17: Overview of energy price scenario developments until 2050 (analytical, not predictive)

Key learnings from Chapter B

- The future development of the European energy landscape, including distributed energy generation (distributed generation), is uncertain. Though the EU has confirmed ambitious goals regarding a greener energy future, implementing this vision will remain a monumental task for years to come.
- The 2050 scenarios depict three possible future settings within which fuel cell powered stationary energy generation has developed to varying degrees.
- There is a strong interdependence between renewables and fuel cells, as both belong to distributed generation and represent viable options for low(er) carbon energy generation.
- The framework conditions that define the scenarios (e.g. policy support for distributed generation and energy efficiency) shape the three depicted future worlds – the confluence of these factors in turn influences the most relevant prices (electricity, natural gas, carbon).
- The scenarios serve as key drivers for the sensitivity analysis (see Chapter E), as the selected, fuel cell relevant factors exhibit varying degrees of realisation and intensity in the three possible worlds.

C. Addressable market, demand drivers and market potential for stationary fuel cell systems

Market overview and segmentation: The market for fuel cell distributed generation

This study aims to assess the market potential of stationary fuel cells by quantifying the addressable demand as well as potential market shares within reach. The market is divided into three different market segments: residential, commercial and industrial.

- **Residential segment** comprises one- and two-family dwellings (1/2-family dwellings)
- **Commercial segment** comprises both residential (i.e. apartment buildings) and non-residential buildings⁵² (i.e. education buildings, health buildings, industrial buildings, storage buildings, office buildings, commercial/retail buildings, agriculture buildings and other buildings)
- **Industrial segment** comprises industrial facilities where fuel cells are applicable such as breweries, wastewater treatment facilities, data centres, etc.

Given that the main demand drivers differ amongst market segments, we use a market-sizing approach that is driven by the residential and commercial construction market on the one hand and a bottom-up market-sizing approach with industry-specific modelling techniques on the other hand.

In order to precisely identify and carefully prioritise the overall addressable markets for stationary fuel cell applications, the study ranks the markets in terms of accessibility. As a result we identified primary, conversion and tertiary markets for stationary fuel cell commercialisation in both the industrial and commercial segment.

- **Primary markets** for residential fuel cell CHP solutions embrace buildings with currently installed gas-fuelled heating technologies (i.e. gas boiler, internal combustion engine, Stirling engine, etc.) due to the lower switching costs for residents already connected to the gas grid
- **Conversion markets** are also attractive for fuel cell commercialisation. However, switching costs may pose an important hurdle. The conversion market category comprises buildings with non-gas fired heating solutions such as heat pumps, wood (pellet) boilers, oil-fuelled boilers and coal-fuelled heating technologies
- **Tertiary markets** are the least attractive for fuel cell commercialisation, including households reliant on district heating (due to high contracting time required and typically very competitive pricing), power (due to difficulty of substitution for e.g. electric floor heating) and biogas & other biomass (niche segments with very specific power and heat requirements)

⁵² **Education** buildings: schools, colleges, universities, buildings for scientific research purposes; **Health** buildings: hospitals, clinics, medical centres and other medical facilities; **Industrial** buildings: buildings for energy generation and distribution, buildings for water production and distribution, buildings for sewage and waste disposal, workshops, factories, slaughterhouses, breweries, assembly halls etc.; **Storage** buildings: warehouses, magazines, storehouses, cold storage warehouses, logistics buildings; **Office** buildings: office and administration buildings, courthouses, parliament buildings, bank buildings, publishing houses; **Commercial** buildings: retail and wholesale buildings, shops, supermarkets, department stores, shopping centres, market and fair halls, auctions halls, petrol station buildings; **Agriculture** buildings: buildings for the storage of agricultural machines or equipment, barns, silos, granaries, greenhouses, cattle sheds, wine cellars; **Other** buildings: buildings for communication and transport purposes like data processing centres, station buildings, multi-storey car parks or hangars, restaurants, kindergartens and day-care centres, cinemas, museums, congress halls, zoo buildings, gyms, stadium buildings, prison buildings etc.

In the industrial segment the addressable market and market prioritisation is assessed on a use case basis and varies in definition accordingly.

Methodology: Quantifying the residential and commercial market segments

The construction market (new builds and renovations) is the main driver for heating technologies in the residential and commercial segments. We use a market model based on a three-step approach to identify the annual market potential for fuel cell technologies:

1. **Conducting as-is assessment** – Exhaustive understanding of the as-is situation of both building stock and new buildings, covering both building types and corresponding heating solutions;
2. **Defining replacement cycles** – Annual calculation of the number of heating system exchanges/ installations necessary, given the lifetime of heating solutions;
3. **Forecasting market shares** – Forecast of future market shares of heating solutions until 2050 under different scenarios.

Step 1 – Conducting as-is assessment:

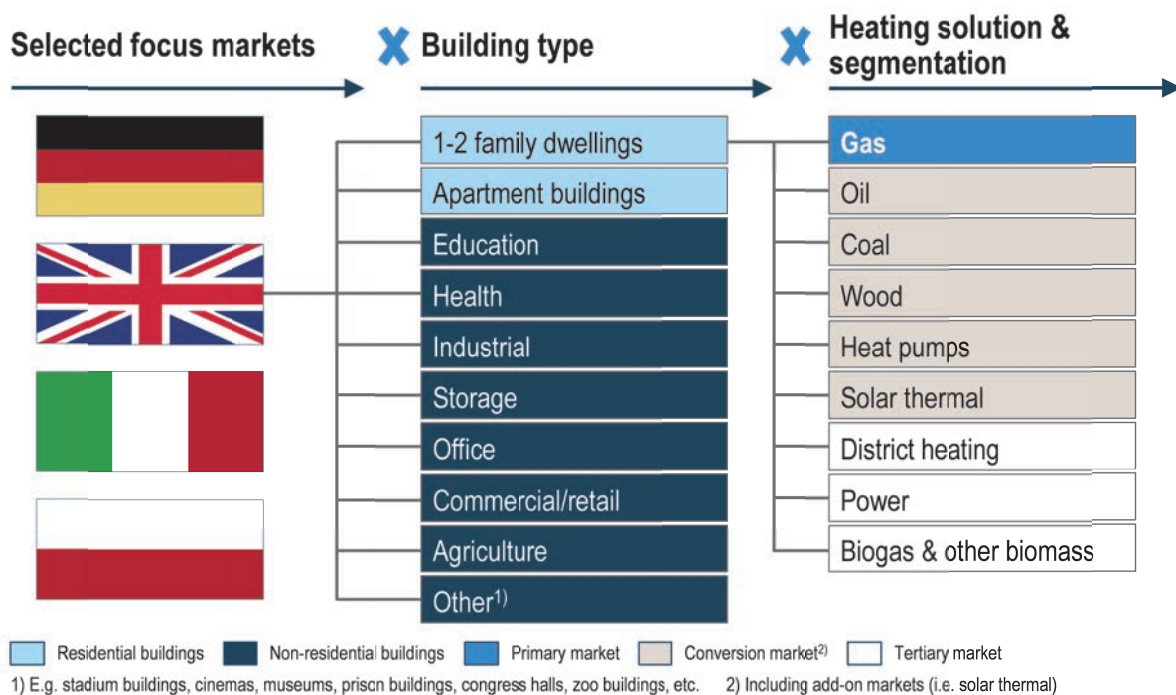


Figure 18: Market segmentation by relevance for stationary fuel cells – Illustrative

In order to achieve a comprehensive assessment of the as-is situation, we identify the total number of buildings by building types (Figure 18) and the corresponding split of heating solution per building type. We make extensive use of data from national statistical institutes, government publications and research institutes (e.g. Euroconstruct). The objective of the initial assessment exercise is to identify the number of buildings of a certain type in a specific country using a specific heating technology. In the residential sector, additional specific characteristics such as building age, degree of renovation, average number of dwellings per building type, demolition rate and central heating share are available. This type of detailed market segmentation facilitates the identification of primary, secondary (conversion) and tertiary markets for fuel cell technologies – in the order of penetration likelihood. Solar thermal collectors are add-on solutions for heat generation (especially hot drinking water). Since solar thermal is not a primary heating solution, we regard it as a separate cluster.

Step 2 – Defining replacement cycles: The objective of the lifetime computation exercise is to generate annual figures for the total number of replacements/installations expected in each year. The approach is different for building stock and new buildings.

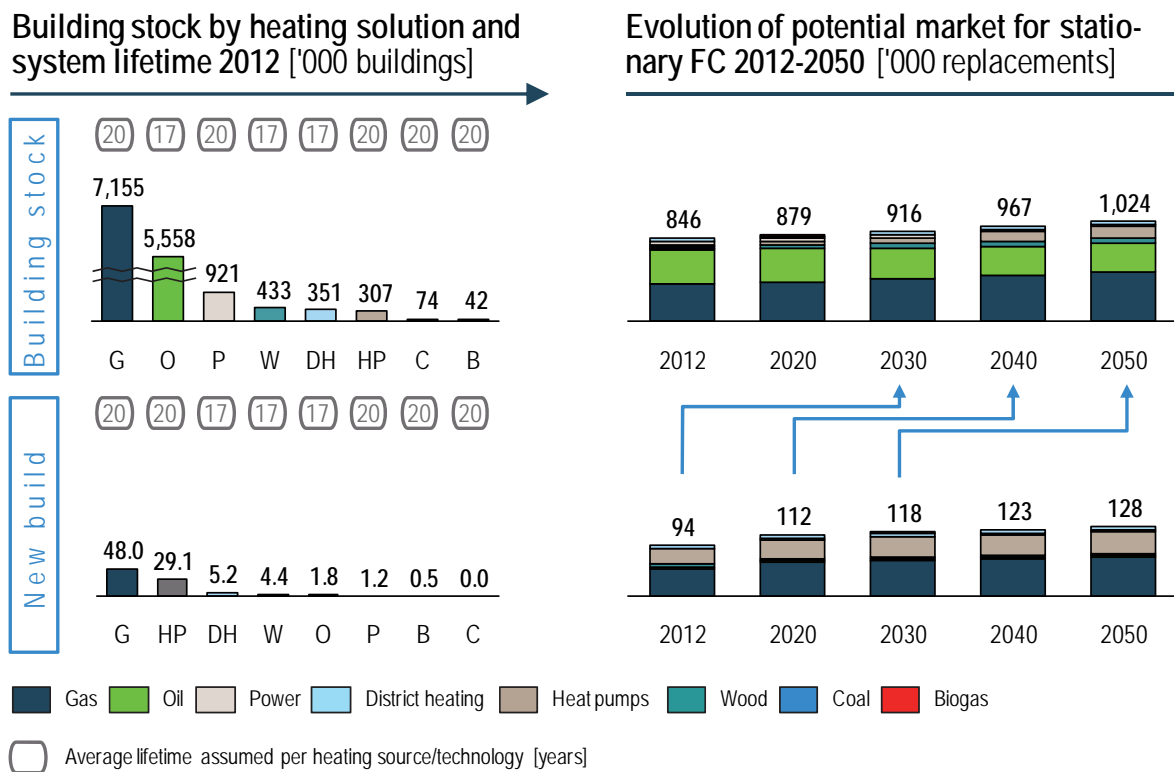


Figure 19: Potential market for fuel cells in German 1/2-family dwellings – Illustrative example⁵³

For the building stock approach, a linear projection of the system lifetime is used to simulate the total number of system replacements expected (see Figure 19). The main assumption is that at the end of the system lifetime, the user re-enters the market, facing a compulsory decision to renew or replace the existing heating technology. The new buildings approach simulates the number of new buildings choosing a certain heating technology, based both on historical data and industry forecasts. New buildings, however, become part of the building stock once constructed and thus become – from a modelling perspective – part of the building stock once the lifetime of their corresponding heating systems concludes.

Step 3 – Forecasting market shares: The third step of our modelling approach simulates the decisions for and against possible heating solutions taken by building owners until 2050. It thereby provides a simulation of trends for heating technologies (see Figure 19). The objective of the forecasting exercise is to model the evolution of market shares for heating technologies via renewal and replacement decisions and the inter-switching of heating technologies (i.e. by weighting the relevant technology pool per existing heating technology installed). The simulation is based on the economic and environmental benchmarking exercise of this study, existing forecasts from leading national and international research and industry centres and expert interviews.⁵⁴ The forecast also regards the development of the construction sector by 2050 in the four focus markets.

⁵³ Demolition of buildings as well as buildings without heating solutions excluded from the assessment. Abbreviations of heating sources/technologies as follows: gas (G), oil (O), power (P), district heating (DH), heat pumps (HP), wood (W), coal (C), biogas (B).

⁵⁴ Cf. Euroconstruct (2013), Oxford Economics (2014), Royal Dutch Shell (2013)

Residential market segment: Status quo, future development, demand and fuel cell potential

The residential market segment comprises 1/2-family dwellings in the four focus markets. On the following pages we describe the building stock and highlight the most important national characteristics such as: age of buildings, degree of insulation, most popular heating solutions, construction of new 1/2-family dwellings and the overall outlook. After describing the current situation, the study proceeds to illustrate the total addressable market for stationary fuel cell technologies.

1/2-family dwellings – status quo

When considering the demand potential of stationary fuel cells in residential buildings – here specifically 1/2-family dwellings – we focus on the majority product type in the European portfolio, i.e. integrated, heat-driven fuel cell mCHPs targeting the heating market. Main competitors are thus conventional heating solutions; homeowners face the inevitable decision of a technology solution to heat their home. The market for add-on, power-driven base-load fuel cells is different as it mainly concerns investment cases for distributed power generation. Here, fuel cells typically compete with other power generation solutions like solar PV.

The 1/2-family dwellings sector is by far the largest sector in the European building stock, accounting for 73% of the total building stock in Germany, 65% in the UK, and 67% in Italy and Poland.⁵⁵ In this context, Germany is the largest market for 1/2-family dwellings in Europe, with approximately 15 m buildings and 18 m dwellings in total. Naturally, the total size of the 1/2-family dwellings sector (i.e. total number of buildings) is highly correlated with the total population in the underlying market. Hence, Germany is followed by the UK, Italy and Poland in terms of relative magnitudes.

The vast majority of the buildings were built in the period between 1950 and 2004 (68% of 1/2-family dwellings in the UK, 66% in Germany and Poland and 63% in Italy). Italy accounts for the highest share of 1/2-family dwellings built before 1950 (35%), compared to Poland (25%), Germany (26%) and the UK (28%). As a result, Poland and Germany feature the largest share of 1/2-family dwellings built after 2004 with 9% and 8%, respectively. Italy lags behind in terms of new 1/2-family dwellings which only account for 2% of the building stock, half of the share perceivable in the UK. Out of the buildings older than 2004 with highest insulation standards, Italy leads the way with a 50% share of fully insulated 1/2-family dwellings, followed by Germany with 34%, the UK with 27% and Poland with 19%.⁵⁶

The predominantly chosen heating solutions vary significantly amongst the focus markets. Gas is the most prevalent solution in the UK, where approximately 80% of buildings are heated with gas-fuelled technologies. A similar dependency on gas can be found in Italy, where approximately 60% of 1/2-family dwellings use gas as primary heating solution. In Germany, gas remains the most frequently used primary heating source, but with a share below 50%. In Poland, due to the proliferation of district heating, gas only accounts for 7% of 1/2-family dwellings' heating choice (see Figure 20).

Furthermore, the relatively high shares of oil-fuelled heating systems in Germany and the UK are noteworthy. The reason for the strong role of oil is its traditional price competitiveness, especially throughout the second half of the 20th century when most of the existing building stock was constructed.

⁵⁵ Information based on national statistic institutes and specialised research reports (i.e. DESTATIS, Istat, UK Department of Energy and Climate Change, Tabula, Ecofys, Polskie Budownictwo)

⁵⁶ For more information, please refer to Episcopo, The Department of Energy and Climate Change, Tabula, VDI, DESTATIS, ECEEE, Austrian Energy Agency and the IWU

In Italy, wood is a widely spread heating solution. It is also increasingly perceptible in Poland. Coal-based heating technologies are prohibited in Italy and are quickly disappearing in Germany and the UK. However, coal is the most popular heating source in Poland due to its abundant domestic supply. The proliferation of district heating in Poland is historically explainable by pre-1990 energy policies in which district heating was a strategic priority.

Solar thermal becomes increasingly relevant in countries with warm climate, such as Italy and Spain. However, other countries (and even individual states) with particularly high energy-efficiency standards for new buildings are also increasingly adopting solar thermal. In the German new buildings for instance, solar thermal may even be a quasi-mandatory add-on for gas condensing boilers.

An increasingly clean power supply enables a preferable environmental performance of electric heating solutions. Heat pumps have thus been gaining momentum over the past years. The growing deployment of heat pumps confirms the European trend towards a decarbonised electricity supply. In Italy, heat pumps already cover 11% of the market and become increasingly relevant in Germany too, although the environmental benefits remain unclear for the time being.

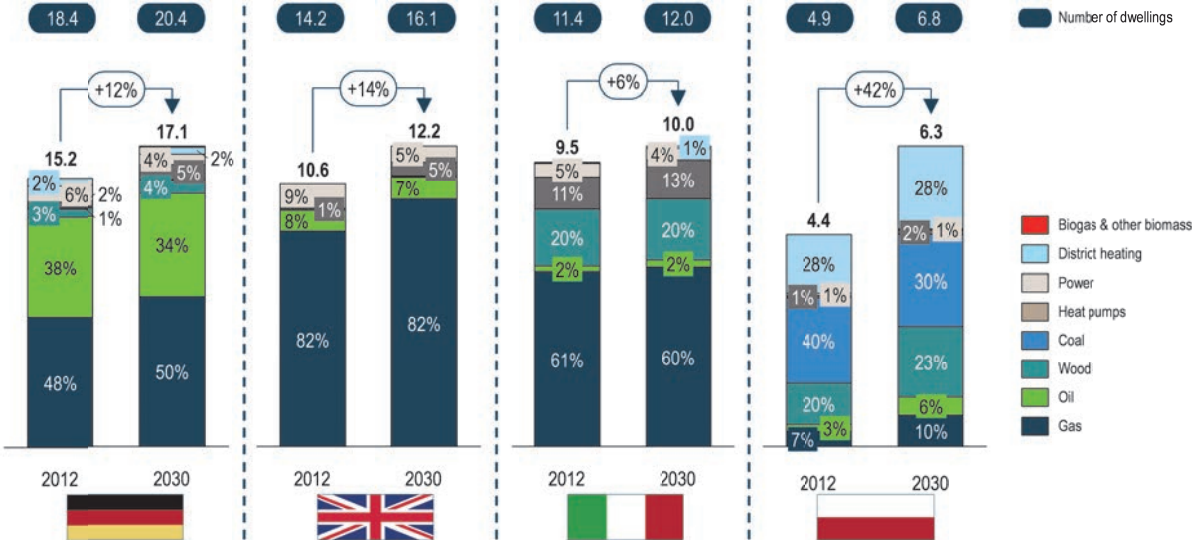


Figure 20: 1/2-family dwellings in all focus markets – number of buildings and heating structure⁵⁷ [m units]

1/2-family dwellings – future development

Figure 20 illustrates the current heating structure and expected development across the four focus markets. Overall, a clearly distinguishable trend of decreasing coal-, oil- and power-based heating solutions is anticipated across the four focus markets. District heating is expected to marginally increase. Gas-based heating technologies, as well as wood-based technologies and heat pumps are expected to experience a positive development both in absolute and relative terms, with few exceptions.

The development of the heating structure is driven by three main factors which have a direct impact on the development of the addressable market for fuel cell technologies:

- The **development of the building stock**, driven by the construction of new buildings
- **Heating technology installations in new buildings**
- **Switching of heating technologies in the building stock**

⁵⁷ Given that the segment also includes 2-family dwellings, the number of dwellings exceeds the number of buildings in all focus markets

Development of the building stock: The European construction market is slowly recovering after the crisis of 2008. However, the pace of recovery and overall residential construction outlook differ amongst the focus markets. Poland and the UK are expected to have the most important development in the 1/2-family dwelling construction segment, exceeding German numbers by 2030.

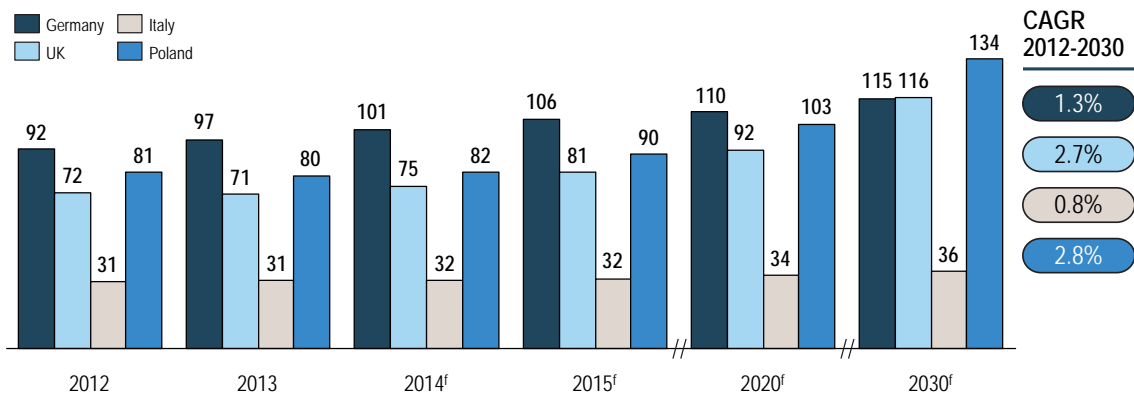


Figure 21: Future growth in newly built 1/2-family dwellings in all focus markets ['000 buildings]

Unsurprisingly, the heating structure of newly built 1/2-family dwellings is different to that of the building stock in the four focus markets. In terms of building performance, some countries, such as Germany, have already pursued a concrete energy efficiency policy for new buildings. The latter requires buildings to fall below a predetermined benchmark heating value.⁵⁸ Whilst some countries are still struggling with the implementation of EU regulation on energy efficiency,⁵⁹ it is not unlikely that upper limits on heat demand will become more commonplace in the European residential sector.

Heating technology installations in new buildings: Overall, gas is gaining momentum. The share of gas-fuelled technologies in Poland was 17% in 2012, significantly above the building stock share of 7%. In Germany, 52% of newly built 1/2-family dwellings chose a gas-fuelled heating technology as their main heat source in 2012, compared to 47% in the building stock. The UK extends the 80% gas-share from the building stock to the new-buildings sector, whereas in Italy only 43% of newly built 1/2-family dwellings choose gas as primary heating solution.

Conversion technologies such as coal and oil are losing importance across the focus markets. Coal-fuelled residential heating is prohibited in Italy and is close to extinction in Germany and the UK. Poland is the only focus market in which coal has established a significant and persistent presence in the selection pool of newly built 1/2-family dwellings.

Only 3% of newly built 1/2-family dwellings in Germany choose oil-fuelled heating technologies as primary heating solution (compared to 38% in the building stock). The UK is the only market in which oil-fuelled heating technologies have a similar share in new buildings as in the building stock (i.e. approximately 8%).

Other conversion technologies such as heat pumps and wood-based heating technologies are also gaining momentum. In Germany, for instance, 32% of newly built 1/2-family dwellings choose heat pumps as their primary heating technology. The Italian market benefits from a particularly high efficiency of the heat pump due to the favourable climate conditions. Furthermore, the comparatively clean power mix in Italy renders the heat pump environmentally friendly. The heat pump is also gaining ground in the UK, mainly thanks to government incentives. In Poland, the heat pump market is at incipient levels.

⁵⁸ For deeper insights into the political benchmarks surrounding German energy efficiency policy, please refer to the EnEV 2009 and 2014.

⁵⁹ Cf. European Commission (2010)

Switching of heating technologies in the building stock: Considering the results of the benchmarking exercise performed in the course of this study as well as market reports on heating technologies, we generally anticipate the switching behaviour of European households to make a balanced move towards environmentally non-invasive solutions. Thus, households currently relying on oil are expected to slowly move towards other solutions (particularly gas). Coal is an unsustainable heating solution in the residential sector and will thus decrease considerably. As a result we expect European gas supply in households to pick up, and to witness favourable developments in the market for gas-based heating solutions in general. Furthermore, the market penetration of heat pump will increase. In those markets where heat pumps have already established a perceivable presence, the switching rates will be higher. Furthermore, we expect district heating to become increasingly relevant, particularly in urban areas. Other alternatives to fossil heating systems, such as wood-based systems (especially pellets) are also expected to gain popularity, though the magnitude of the switching rates is closely associated with wood price developments.

1/2-family dwellings – demand

The largest primary market for stationary fuel cells in the 1/2-family dwellings segment lies in the UK, where approximately 792,000 gas boiler replacements are due in 2012. Assuming an average size of the fuel cell system of 1 kW_{el}, the total addressable primary market is approximately 792 MW_{el}. In 2030, the market is expected to increase to 904,000 replacements and 904 MW_{el}. The size of the primary market in Germany and Italy is very similar, with more than 400,000 units annually. Poland is the smallest potential primary market with approximately 40,000 units annually, increasing to 70,000 units by 2030.

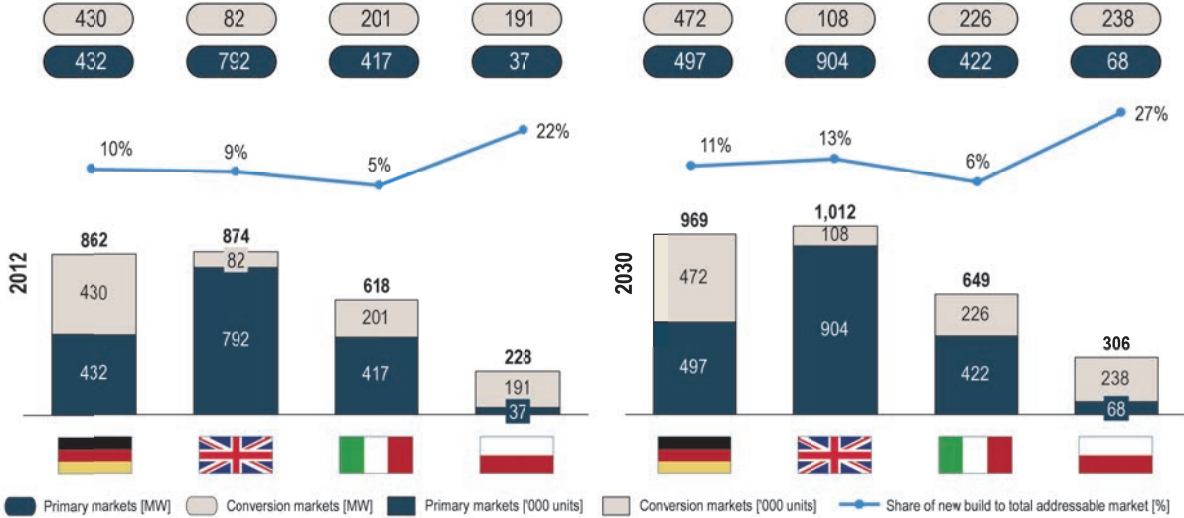


Figure 22: Addressable market for fuel cells in 1/2-family dwellings [MW_{el}; '000 units]

The German conversion market is dominated by oil-fuelled heating technologies close to reaching the end of their lifecycle (approximately 80% of the total conversion market). Wood and heat pumps account for most of the remaining 20%. Oil-fuelled heating solutions also dominate the conversion market in the UK. More than 90% of heating technology exchanges in the conversion market are performed by owners of oil-fuelled technologies. In Italy, wood is the most important conversion market (60% of total conversion market), followed by heat pumps (30%). Poland's dependency on coal also occupied a prominent position within the conversion market segment. Out of the 190,000 annual heating technology exchanges, approximately 100,000 are derivative of coal-fuelled heating solutions. Wood is the second most important conversion market, with 75,000 exchanges, followed by oil with approximately 10,000.

The total market potential illustrated in Figure 22 encompasses both heating technology replacements within the building stock and the total number of new buildings in the four focus markets. Notably, the

market potential generated by newly built 1/2-family dwellings accounts for less than 10% of the total addressable markets in Germany, the UK and Italy.

BOX 1: The Netherlands as another target market for stationary fuel cells

The Netherlands offer promising conditions for the deployment of stationary fuel cells for distributed generation. Stationary applications of fuel cells and other hydrogen energy technologies already receive attention in the Netherlands, e.g. with the set-up of the DutchHy coalition and the state-of-the-art, Rotterdam based hydrogen plant HYCO-4.

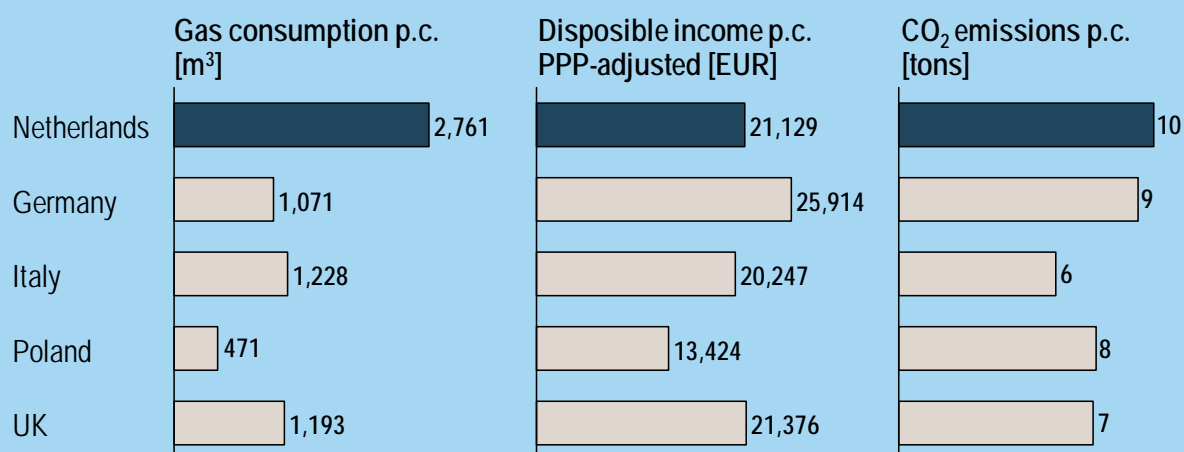


Figure 23: Key indicators of the selected European heating markets⁶⁰

The Netherlands have the most developed gas transmission and distribution network in the European Union, achieving the highest penetration of all member countries. Nearly 36,500 km of high pressure (greater than 40 bar) and close to 100,000 km of low pressure (8 bar) grid transmitted nearly 37 bcm of natural gas for consumption in 2013 according to the most recent BP Statistical Review of World Energy. Households account for ca. 20% of the total national consumption every year, given the widespread reliance on gas for heating and cooking. The comparatively high per capita consumption is exemplary of the high demand for natural gas, displayed in Figure 23. The extensive gas network, as well as the broad prevalence of central heating systems in residential buildings, makes the Netherlands a very attractive market for on-site CHP technologies, particularly the fuel cell with its high total efficiency. In consonance with the transition to a decarbonised energy production in the Netherlands, the elaborate gas network further opens the possibility for flexible and environmentally non-invasive, decentralised power production to complement increasing shares of variable renewables. Decentralised generation already represents over 60% of the total CHP capacity installed. Highly efficient fuel cell power generation may prove imperative in this respect.

Comparatively high disposable income and the necessity to further reduce CO₂ emissions reductions represent further reasons for the high attractiveness of the Dutch market. The real adjusted gross disposable income is displayed in Figure 23. On the whole, Dutch citizens have a 5% higher disposable than their European neighbours. Furthermore, as an EU member state, the Netherlands are committed to reducing annual CO₂ emissions to 20% of the 1990 levels by 2020. As shown in Figure 23 current per capita emissions are comparatively high in contrast to the European focus markets of this study. Given that the Dutch residential sector accounts for 16% of the emissions from electricity and heat consumption, there is significant potential for further reductions with low-emission technologies

⁶⁰ All figures for 2012. Cf. EIA (2014), Eurostat (2014)

such as fuel cells. However, given a 65.5% share of natural gas in the national power mix, the emissions per kWh from the grid (370 g CO₂/kWh) are considerably lower than in neighbouring European countries such as Germany. On the one hand, this circumstance is a testament to Dutch environmental consciousness. On the other hand it limits the room for emissions reductions with fuel cells – until the gas grid decarbonises, for example through biogas or power-to-gas.

Commercial market segment: Status quo, future development, demand and fuel cell potential

The commercial market segment comprises both residential (i.e. apartment buildings) and non-residential building categories (i.e. education buildings, health buildings, industrial buildings, storage buildings, office buildings, commercial/retail buildings, agriculture buildings and other buildings).

Apartment buildings – status quo

When considering the demand potential of stationary fuel cells in commercial buildings (incl. apartment buildings) we focus on integrated, heat-driven fuel cell CHP solutions that aim at the heating market. Main competitors are thus conventional heating solutions; consumers face the inevitable decision of a technology solution to supply heat to the building. The power-driven market for add-on base-load fuel cells is different as it mainly concerns investment-cases for distributed power generation. Here, stationary fuel cells compete with other power generation solutions like solar PV.

The apartment building sector is by far the largest in the commercial market segment, accounting for 55% of total building stock across all focus markets. The overall structure of apartment buildings differs amongst focus markets, especially in terms of average size per apartment building. Amongst focus markets, Poland has the largest apartment buildings averaging 10 dwellings per building, followed by Italy with 8 dwellings, Germany with 7 dwellings and the UK with 3.5 dwellings.

The heating structure in the apartment building sector is similar to that of the 1/2-family dwellings sector. Both are strongly correlated with the national energy resources. However, particularities can be identified in the apartment buildings section, especially with regard to the increased share of district heating and only minor share of heat pumps, compared to 1/2-family dwellings.

The largest primary markets for stationary fuel cell technologies in apartment buildings remain the UK, Italy and Germany. Poland's gas share in apartment buildings is significantly superior to the gas share in 1/2-family dwellings.

In Poland, district heating has a dominant market position, with several local district heating systems being powered with coal. Solar thermal collectors play a minor role in the apartment segment. On the one hand, high investment costs preclude the decision to invest in this technology. If multi-family homes require the decision to make this investment to be made by the residents unanimously, the decision may be deterred due to lacking consensus amongst the parties involved. On the other hand, solar thermal heat generation infrequently translates into direct savings, given physical restraints on the available surface area for collectors in several apartment buildings. This makes the technology even less attractive to homeowners.

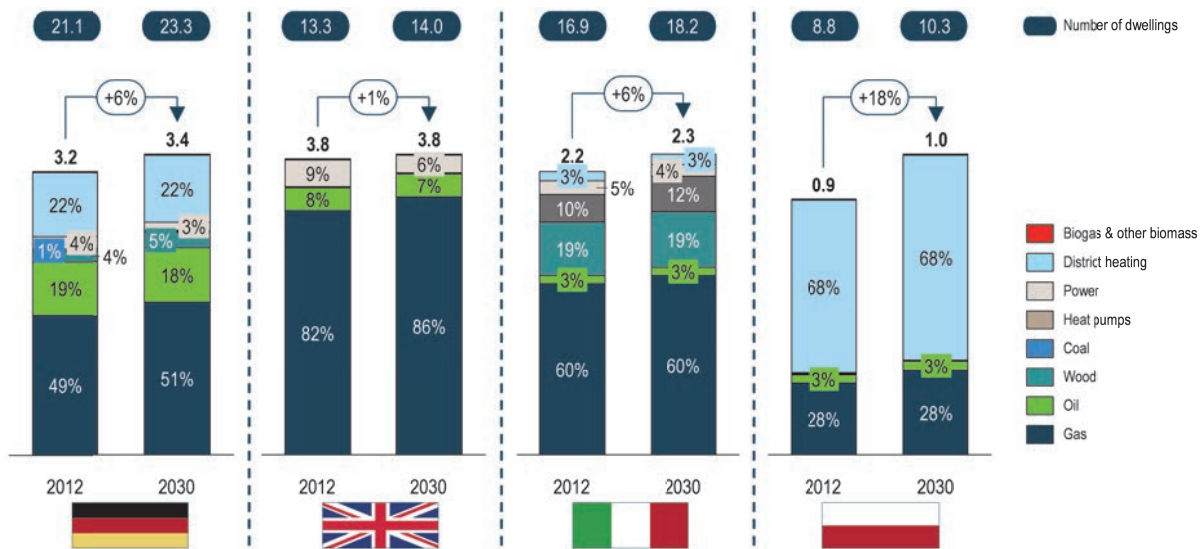


Figure 24: Apartment buildings in focus markets – number of buildings and heating structure [m units]

Apartment buildings – future development

The heating structure in apartment buildings is expected to change moderately across focus markets. In Germany, the UK and Italy, gas is expected to further expand its dominant position. District heating may also increase in absolute terms across the focus markets. However, oil and power are expected to yield market shares until 2030, with the exception of Poland.

As regards the construction outlook, Germany's and Poland's apartment buildings construction are expected to grow at above 2.5% CAGR until 2030. This is consistent with the urbanisation trend in the two countries and the forecasted GDP performance. Italy is expected to decrease its apartment building construction by 20% until 2015 (compared to 2012) and stabilise at 0.6% CAGR until 2030.

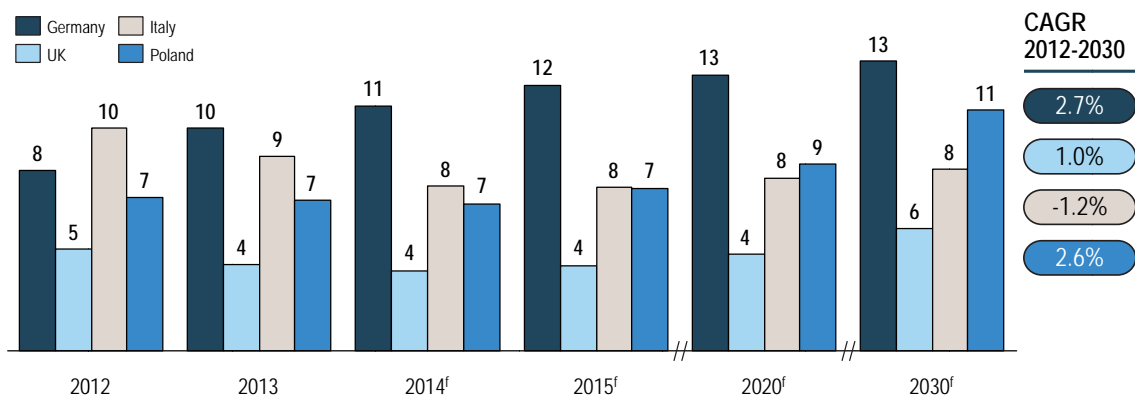


Figure 25: Evolution of apartment buildings new builds ['000 buildings]

Apartment buildings – demand

The UK is the most attractive primary market for stationary fuel cell systems in apartment buildings. Conversion markets such as oil, wood and heat pumps also create important market potential for fuel cell systems.

Figure 26 illustrates the size of potential markets (primary and conversion markets) per country, both from a number of units as well as a total installed capacity perspective. In the four focus markets, there is an estimated annual primary market potential of 1.69 GW_{el} installed capacity (derived from existing gas-fuelled heating technologies) and conversion market potential of almost 0.59 GW_{el}. Until 2030, the

primary market potential could reach 1.77 GW_{el}, whilst the conversion market may increase to 0.62 GW_{el}.

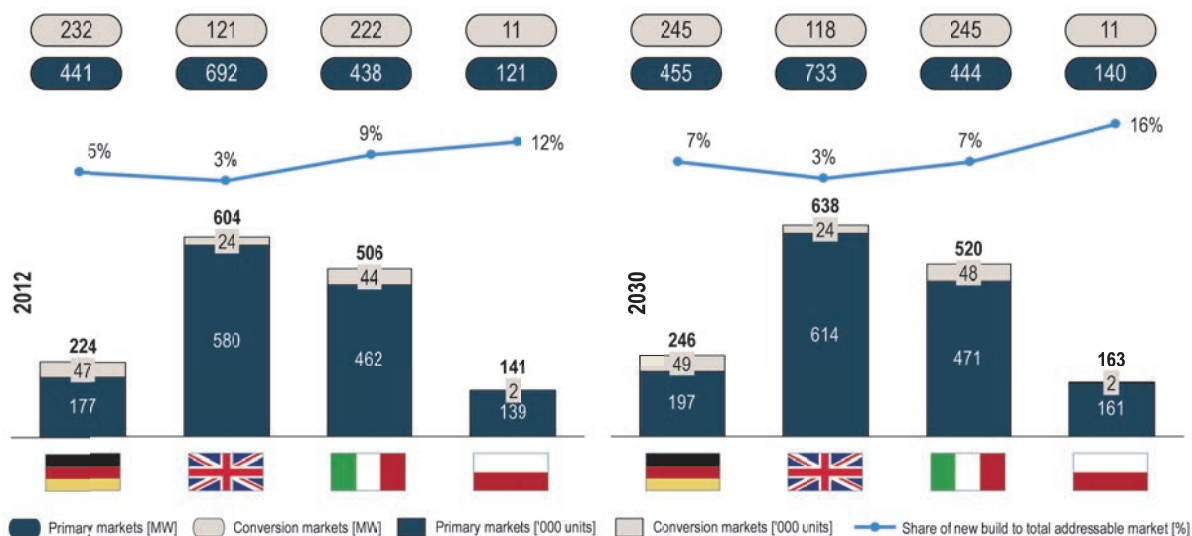


Figure 26: Addressable market for fuel cells in apartment buildings [MW_{el}; '000 units]

Relative to the UK and Italy, Germany exhibits a relatively small market as concerns annual exchanges of heating technologies (i.e. number of units). However, when assessing the market in MW_{el} installable capacity, Germany reaches UK values and even exceeds them in 2030 – as explained by the structural characteristics of the German apartment building sector.

German apartment building stock is characterised by large share of central heating (i.e. one heating system and supply per building) and longer lifetime of gas boilers (i.e. approximately 20 years). We estimate that only 20% of apartment buildings in Germany operate with distributed heating systems (i.e. separate heating systems per apartment/floor), which is significantly below the UK, where more than 70% of buildings use distributed heating systems. Also, gas boilers in Germany have a 33% higher lifetime compared to the UK which translates into a smaller number of annual replacements. In terms of heating infrastructure, the vast majority of Polish buildings operate on a central infrastructure. This becomes particularly clear with regard to the district heating share of 68%.

In order to allow for segment comparison (i.e. residential vs. commercial vs. industrial) we have used average sizes for decentralised and central heating technologies. For the small decentralised segment to supply single apartments or floors, we assume a 0.7 kW_{el} average installable capacity (i.e. the lower end of available systems for residential 1/2-family dwellings that have already been installed in German apartments several instances). For large central units to supply entire buildings we assume a 5 kW_{el} average capacity.

In this sense, the UK and Germany are the most promising potential markets with annual installable capacities of more than more than 810 MW_{el} and 670 MW_{el} respectively (850 MW_{el} and 700 MW_{el} until 2030), closely followed by Italy with approximately 660 MW_{el} (690 MW_{el} until 2030) and Poland with 130 MW_{el} (150 MW_{el} until 2030).

Non-residential buildings – status quo

The non-residential building structure is dominated by agriculture, commercial, storage and industrial buildings. Buildings with more sophisticated power and heat demand such as health care buildings (which include hospitals), education buildings and office buildings amount to less than 10% of the total non-residential building stock.

The non-residential segment is highly heterogeneous both in terms of the overall power and heat requirements as well as the complexity of the decision process.

Within the non-residential buildings segment there are building types which, due to their usage, do not require heating (especially agriculture buildings, storage buildings and industrial buildings). In Italy, for example, almost 90% of agriculture buildings, 63% of storage buildings and 30% of industrial buildings do not require heat. In Germany, the UK and Poland, given the harsher climatic conditions, shares are slightly smaller (i.e. 80% of agriculture buildings, 55% of storage buildings and 25% of industrial buildings, on average).

The heating structure amongst non-residential building types is also highly diverse. However, two overall conclusions can be drawn from the data analysis so far. Firstly, heating technologies in non-residential buildings are highly influenced by the market-specific heating structure and, secondly, a differentiation between rural and urban buildings can be observed also with respect to the heating structure (i.e. agriculture and industrial buildings are predominantly located in rural areas, whereas health buildings, education buildings and office buildings are predominantly located in urban areas, having more accessibility to district heating, gas infrastructure, etc.).

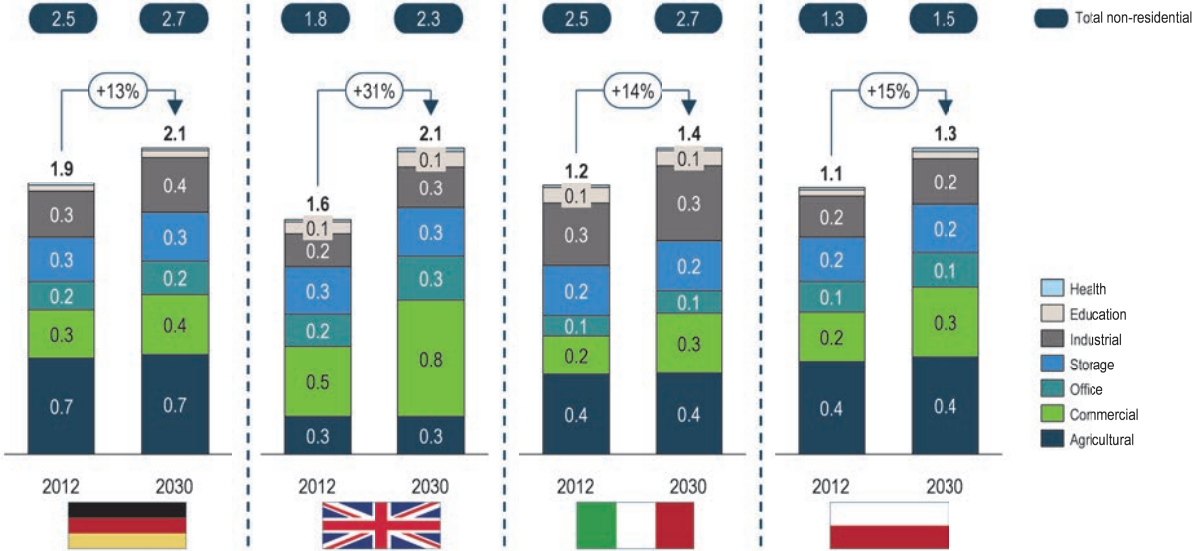


Figure 27: Main building types in the non-residential building stock [m buildings]

Non-residential buildings – future development

The building-type specific evolution of new non-residential buildings is assessed based on two core factors: the overall outlook of non-residential construction in the four focus markets and the performance outlook of the corresponding industries.

In Figure 28 we illustrate the evolution of non-residential buildings in the four focus markets.

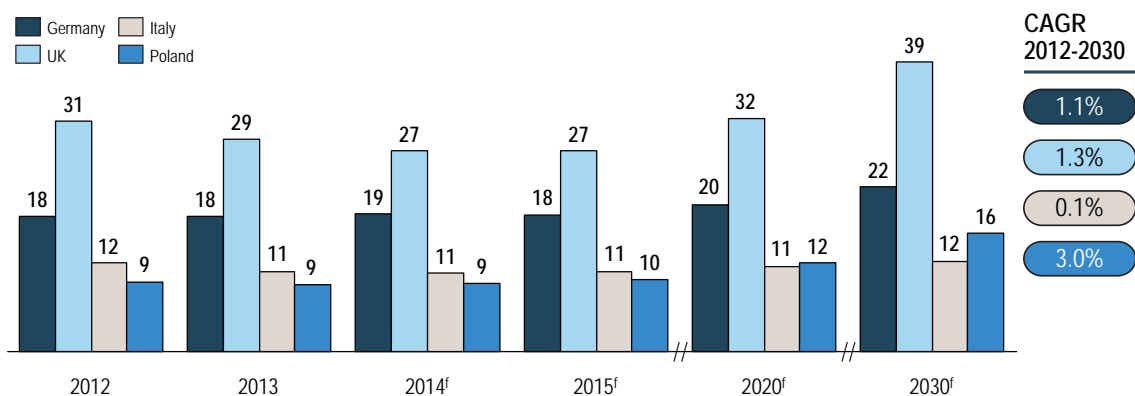


Figure 28: Future growth of non-residential new buildings ['000 buildings]

Office buildings are expected to outgrow the general non-residential market across focus markets, given the growing share of the service sector in GDP. With the exception of Poland, education buildings construction is expected to develop at below 1% annual share, amongst focus markets. Health as well as commercial building construction will grow above non-residential average, across all focus markets.

Non-residential buildings – demand

In total, the non-residential building segment is accountable for a market of approximately 8.5 GW_{el}, across the four focus markets, excluding the 'other building' category (2.3 GW_{el} in Germany, 3.2 GW_{el} in the UK, 2.3 GW_{el} in Italy and 0.7 GW_{el} in Poland). The total primary and conversion market potential may reach 10.1 GW_{el} until 2030. Compared to the residential sector, the share of new buildings in the total market is more significant on average.

Commercial and industrial buildings lead the market in terms of number of units replaced and required capacities. Office buildings are also attractive, especially in the UK and Germany. Poland exhibits a small primary market but has large conversion markets, especially in the industrial buildings.

For the calculation of capacity requirements, the study estimates an average required capacity per building type, across the four focus markets: 5 kW_{el} for agriculture and storage buildings, 25 kW_{el} for commercial/retail and office buildings, 50 kW_{el} for education buildings and 100 kW_{el} for health and industrial buildings.

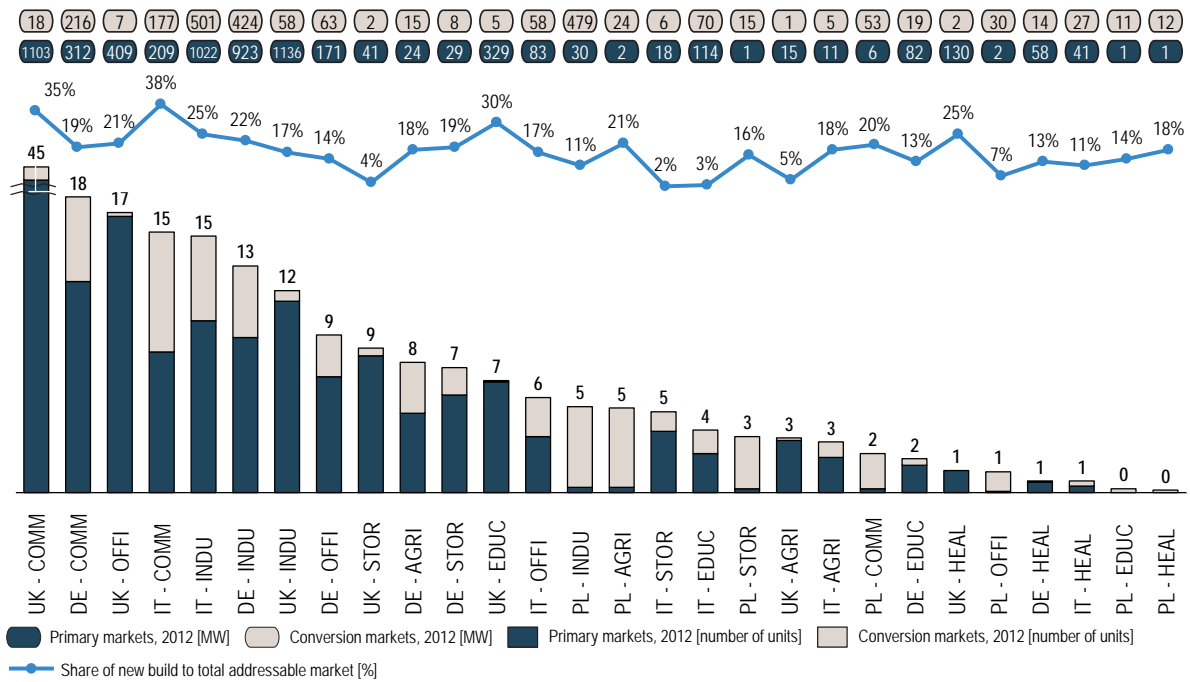


Figure 29: Addressable market for fuel cells in non-residential buildings 2012 [MW_{el}; '000 units]

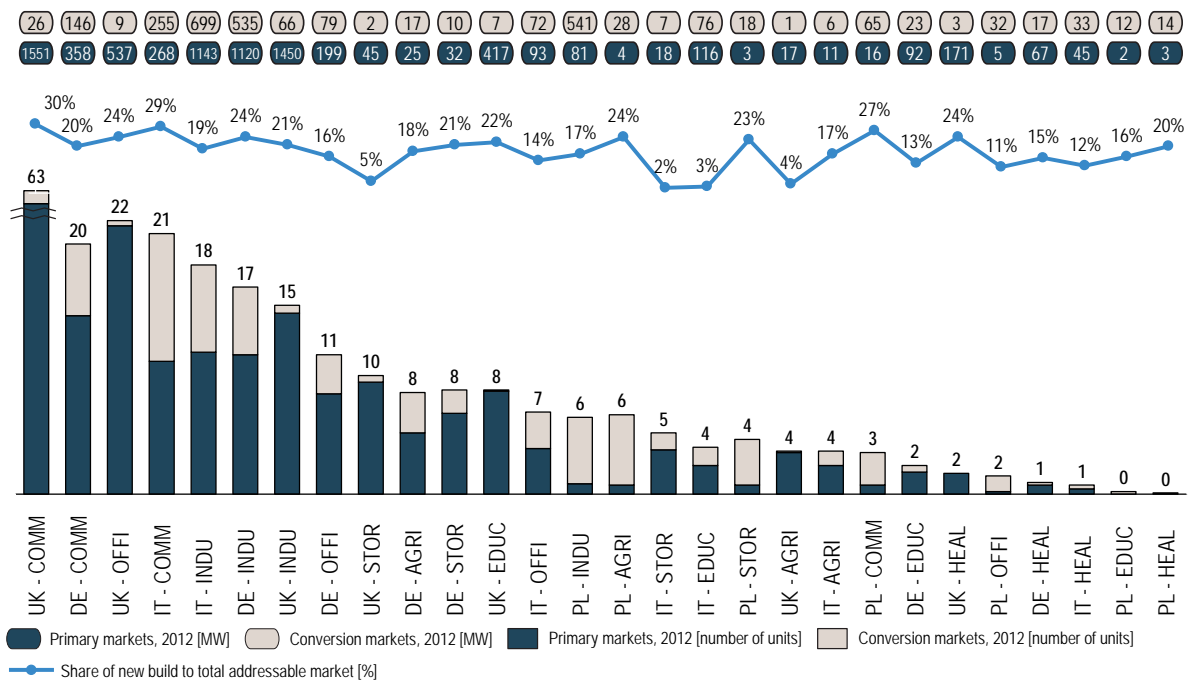


Figure 30: Addressable market for fuel cells in non-residential buildings 2030 [MW_{el}; '000 units]

Figures 29 and 30 illustrate the existing and future addressable market for fuel cell technologies. Commercial and industrial buildings are leading in terms of size (both number of units and installed capacities) and could be highly attractive for fuel cell technologies due to larger size and relatively constant power demand. Office buildings are also attractive, particularly in the UK, but also in Germany and Italy.

Overall, the commercial sector bears the largest market potential in terms of installable annual capacity. However it features in essential parts (e.g. apartment or office buildings) considerably more complex customer settings and purchasing decision making processes, e.g. multiple owners in an apartment or office buildings that have to jointly choose a new heating technology. This may be part of the reason why the European stationary fuel cell industry so far targets the segment using systems that are primarily designed for other customers (e.g. targeting large apartments with smaller units for 1/2-family dwellings) and why larger systems between 5 to 400 kW_{el} stand at a very early stage of product development.

Industrial market segments: Prime power, CHP biogas and CHP natural gas addressable market

Methodology for quantifying the industrial market segment

In the industrial sector, the evolution of the construction market is of minor relevance. Business characteristics are much more important. Clustered according to the main demand drivers, the study differentiates between three application groups for stationary fuel cells:

1. **Power security** (i.e. data centres, base stations, etc.);
2. **Power and heat intensity** (i.e. pharmaceuticals, chemicals, paper production facilities, etc.);
3. **Availability of fuel** (i.e. biogas produced in wastewater treatment facilities, breweries, etc.).

The economic performance is crucial in the industrial sector and predominantly the highest-ranked criteria in the decision making process. Once a new technology exceeds the economic attractiveness⁶¹ of the currently used technology, switching to the new technology becomes highly probable. The study thus bypasses the life-cycle approach of the residential and commercial segments considering the existing base for industrial applications as the addressable market.

The total market potential can be derived from today's installed capacity of distributed generation in the industrial sector. This market volume comprises all applications cited above that have already implemented distributed generation technologies. However, some markets are potentially addressable by the fuel cell but are not included in the distributed generation statistics because there is no implementation yet (except maybe back-up solutions that are not within the scope of this study), e.g. data centres. The totally installed capacity of distributed generation technologies in industrial settings is around 24,393 MW_{el} for all four focus markets. However, most of that capacity is still in use and does not require immediate exchange. For simplification we assume that installations need to be exchanged or refurbished after 10 years. This leads to a fuel cell addressable market potential of around 2,500 MW_{el}. Considering that not all distributed capacities are gas fired the primary market potential is a bit lower, i.e. 1,500 MW_{el} in the focus markets. Figure 31 gives an overview of the described figures.

⁶¹ Considering financial, operational and environmental criteria

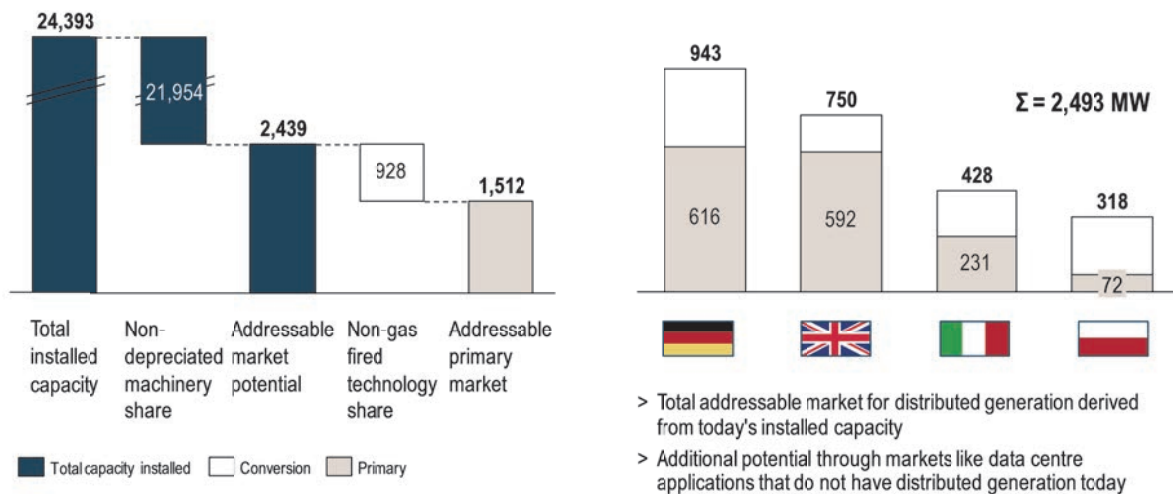


Figure 31: Installed capacity in the industrial sector and addressable market for fuel cells [MW_e]

There is a wide range of potential applications in the industrial market segment (e.g. ICT base stations, food processing facilities, wastewater treatment facilities, refineries, grid-scale CHP or prime power, paper manufacturing facilities, chemical production facilities, healthcare facilities etc.) – not all can be analysed in detail in the scope of this study. For this reason, but also considering the area of expertise of the industry players forming the coalition for this study, we focus on selected industrial applications. However, the hypothesis of this study is that all potential application fields have equally attractive niches and opportunities for stationary fuel cell systems which should be considered as such and analysed in detail.

The most relevant industrial applications (within the three clusters described) for the coalition of this study have been identified by means of a survey. Within the survey, potential industrial applications of fuel cell technologies were identified, collected and weighted according to six criteria: (1) short-term accessibility, (2) near-term market size, (3) long-term market potential, (4) technology maturity today, (5) overall ease of switching/installation, (6) clients' sense of urgency and need for solution. The results of the survey are illustrated in Figure 32.

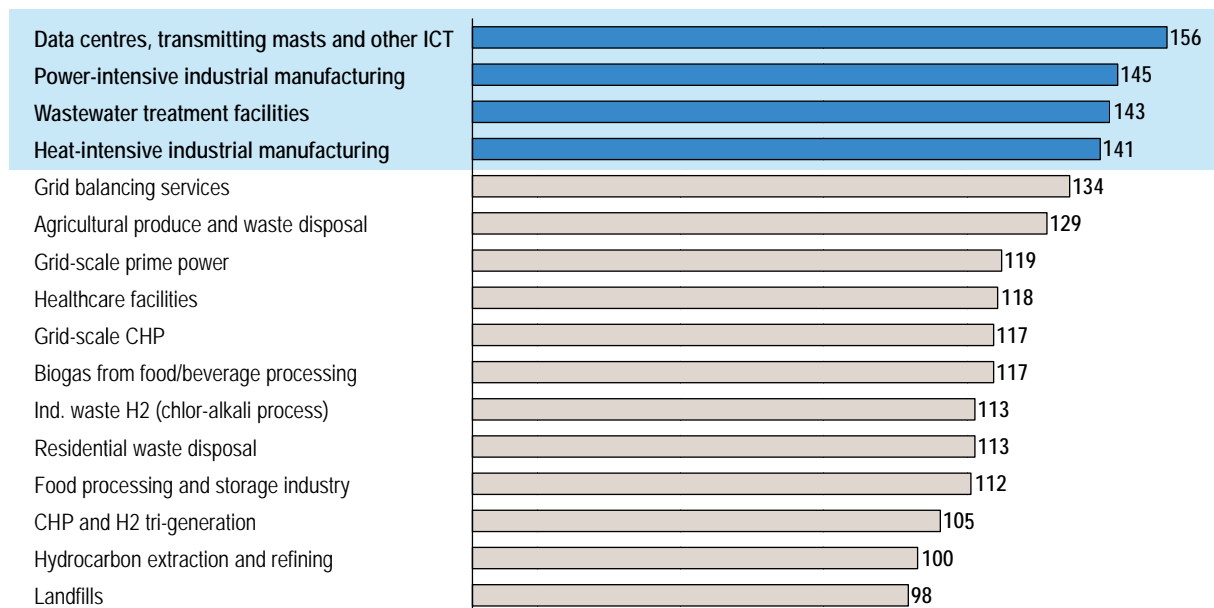


Figure 32: General pool and prioritisation of potential industrial applications for fuel cells

The following highly-ranked use cases are analysed in detail by the study: **data centres** to represent ICT applications, **pharmaceutical & chemical industries** as a representative for power-and heat-intensive industries as well as **breweries** and **wastewater treatment facilities** as representative for the biogas cluster. In order to quantify the addressable market of industrial fuel cell applications, the study uses a bottom-up approach with individual demand drivers for each sub-segment across all focus markets.

Given the lack of rigorous statistical data on distributed power generation, installed CHP, etc., we used a three step approach to estimate the addressable market for fuel cell technologies in the specific sub-segment across all four focus markets:

1. **Total market sizing** – total number of data centres, breweries, wastewater treatment facilities, pharmaceutical & chemical plants;
2. **Prioritisation of sites** – identification of the most attractive segments within the defined use cases (e.g. colocation centres, large breweries, etc.);
3. **Definition of power requirements** – total power consumption and average full load hours per use case;
4. **Estimation of market** – estimation of minimum addressable market for fuel cell technologies in all focus markets, based on information cumulative in the previous steps.

The specific approach for quantifying the market for different industrial use cases is as follows:

- **Data centres:** Based on publicly available information and industry studies we identify the total number of data centres and colocation centres in all focus markets. Due to their larger size and power consumption (i.e. minimum 3,000 servers and potential required installed capacity of approximately 1.4 MW) colocation centres are considered the primary market for fuel cell technologies. Given the total number of colocation centres and the minimum required installed capacity per colocation centre we estimate a minimum primary market in all focus markets. For the future development we use industry studies and expert interviews.
- **Breweries:** The total number of breweries and microbreweries in all focus markets is assessed based on industry studies. Due to their limited power consumption (i.e. up to 1,000 hectolitres per year) we exclude microbreweries from the calculation. Given the total beer production, average power consumption per kWh and the average number of full load hours, the study provides an indication of total required installed capacities in all focus markets.
- **Pharmaceuticals & chemicals:** The study examined national statistics institutes' reports to identify the existing installed capacities for distributed power production in the pharmaceutical & chemical sector, in all focus markets.
- **Wastewater treatment facilities:** Based on publicly available information and industry studies we identify the total number of wastewater treatment facilities in all focus markets. We also identify the number of facilities which use anaerobic digestion and thus produce biogas. Biogas-producing facilities are considered the primary market. Given the biogas production and the average number of full load hours in wastewater treatment facilities, the study provides an indication of the total required installed capacities to utilise the produced biogas in all focus markets.

Prime power systems for data centres

ICT is under the microscope worldwide due to the large amount of greenhouse gas emissions they are directly accountable for. It is estimated that approximately 2% of the worldwide energy consumption is used by ICT industries. Since 2011, the European Commission has been piloting methodologies to

quantify the environmental footprint of ICT in general. The European Commission has also commenced several "smart data centre" projects to increase energy efficiency and improve the footprint.

Data centres have been growing constantly over the past years, mainly due to the global digitalisation trend. A clearly distinguishable centralisation trend can also be identified in the data centres sector as substantial economies of scale can be achieved. It is expected that the average size of data centres in terms of electric capacity will increase to approximately 10 MW in the future.

Usually, 40-60% of power consumption in the data centres is allocated to cooling. Cooling is applied at server and rack level through ventilation and room level through air conditioning. Optimal room temperature for a data centre is 16-18 °C. In order to increase energy efficiency of data centres, several cooling concepts have been under constant review. Liquid cooling has long since exceeded the testing phase and aims at reducing energy consumption in data centres by up to 40%. Even though cooling is a necessity today and a contribution by stationary fuel cells is possible, tri-generation is expected to have marginal benefits in the total energy balance, given the future direct cooling trend.

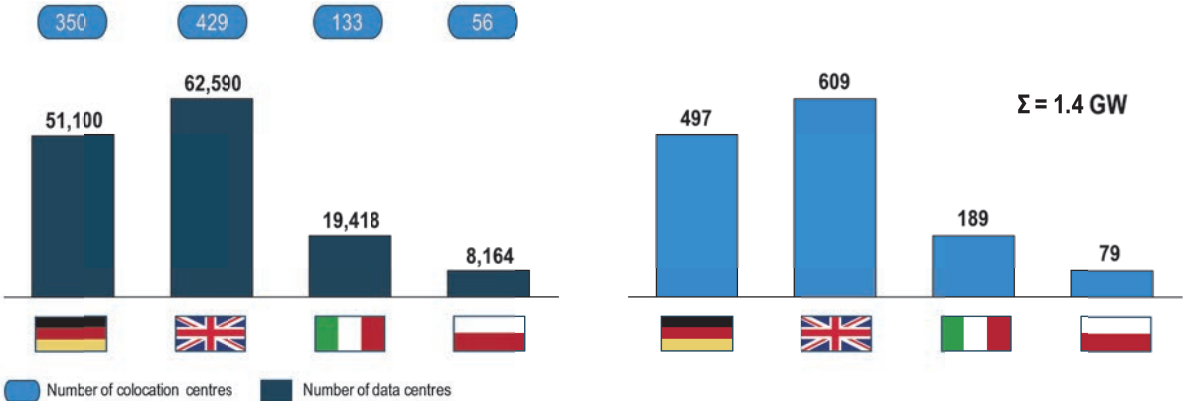


Figure 33: Market structure of data centres and total installed generation capacity [MW_{el}]

The data centre market structure is mostly fragmented across all focused markets and dominated by very small facilities. In contrast, colocation centres are large data centres which usually comprise more than 3,000 servers, and thus require a power capacity of ca. 1.4 MW_{el}. Colocation centres provide space, power, cooling and security for the servers of third parties and are primary market for fuel cell technologies due to their larger size and overall energy efficiency ambitions. Furthermore, as the digital economy advances, reliable power supply becomes increasingly important. This is at the heart of the move towards IT outsourcing and a selling argument for hosting and colocation service providers.

However, colocation services are at incipient levels and are expected to develop substantially on the mid-term as important economies of scale can be achieved. Currently their absolute numbers account for less than 1% of total number of data centres in the four focus markets.

The UK is the largest and fastest growing market for data centres, driven by a high affinity of business to cloud or decentralised data solutions on the one hand, and substantial development in the high level service sector on the other.

In total, we estimate capacity requirements of approximately 1.4 GW_{el} across all four focus markets. The addressable market may have the same volume if a convincing technology option is offered.

CHP natural gas systems for pharmaceutical and chemical production facilities

Pharmaceutical and chemical industries are highly attractive for fuel cell technologies due to several reasons. Firstly, both industries have high demand for power and heat in their production processes. Secondly, the rising electricity prices increasingly drive companies to consider distributed solutions. This also translates into a favourable move towards energy efficiency. Last but not least, power security is

crucial in several production processes. Additional costs for UPS units and back-up generators can hence be avoided.

In some chemical manufacturing processes, hydrogen is a by-product which can be utilised and transformed into heat and power by fuel cell systems (e.g. production process of ammonia, chlor-alkali, etc.). The usage of waste hydrogen is an important competitive advantage of fuel cell systems in general against conventional CHP technologies such as gas combustion engines and gas turbines.

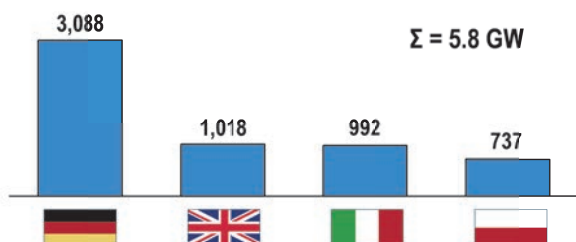


Figure 34: Installed generation capacities in the pharmaceutical & chemical sector 2014 [MW_{el}]

In the pharmaceutical and chemical sector, substantial capacities for on-site distributed power generation are already installed. The total number of plants with installed distributed power capacities is not assessed due to the wide variation in size, plant characteristics and production process heterogeneity. However, in terms of installed capacity, approximately 5.8 GW_{el} of distributed power capacities can be identified across the four focus markets. The sector accounts for 30% of total installed distributed power capacities in Germany, 14% in the UK, and 23% in Italy and Poland respectively. The share of CHP in auto-generation across focus markets is above 50%. The addressable market p.a. depends on the depreciation rates and may amount to 10% of the given volumes.

CHP biogas systems for breweries

Breweries are characterised by a high and complex energy demand. Heat of different temperatures (from 90 to 110°C) is used in different steps of the production process (i.e. brewing process, glass cleaning, heating/cooling of storerooms, etc.). However, heat demand is significantly smaller in breweries with PET and can bottling, which are significantly more power-intensive. Power security is also an important topic for breweries as power shortages can produce significant disruptions along the entire production process. To tackle the risk of power shortage, many breweries use UPS units and back-up generators which imply additional financial burdens.

Breweries can also produce biogas by applying anaerobic digestion processes to wastewater. Approximately 2-6 hectolitres of wastewater are produced for each hectolitre of beer output.⁶² The availability of biogas increases the attractiveness of CHP solutions which can utilise the biogas and transform it into power and heat, thus improving the energy efficiency of the brewery. Biogas produced in breweries contains 79-85% CH₄ and 15-30% CO₂ – approximately 11 kWh of energy fuel can be produced for each m³ of wastewater.

The trend towards biogas generation and installation of CHP solutions has already commenced in some European markets. In Germany, large breweries such as Paulaner, Bittburger, Erdinger and others are successfully operating CHP technology to improve energy efficiency.

⁶² Cf. The Brewers of Europe (2014)

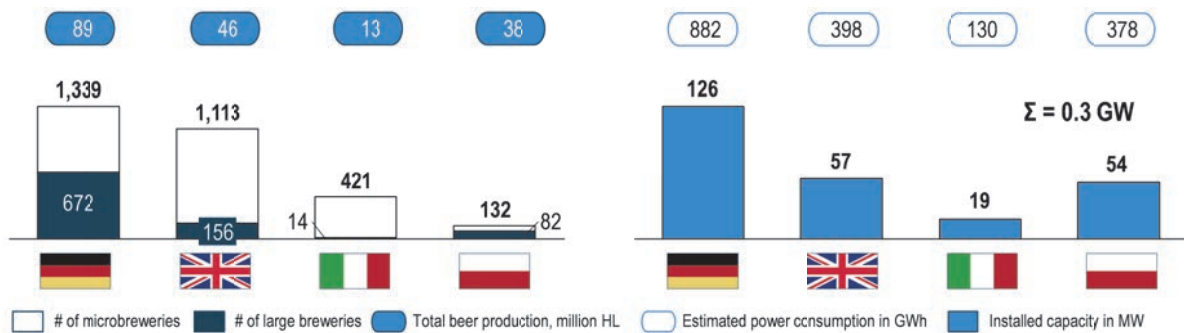


Figure 35: Breweries in the four focus markets, estimated power consumption of large breweries and installed generation capacities in 2014 [MW_{el}]

The brewery landscape is highly diverse amongst the focus markets, strongly entwined with the respective traditions and the cultural values surrounding consumption.

We differentiate between 'microbreweries' and 'large' breweries. Due to their small size of up to 1,000 hectolitres per year, in microbreweries energy efficiency is a less critical issue. Moreover, given their limited output, the required infrastructure for anaerobic digestion would not be economically viable.

In terms of beer output, Germany leads the European beer production with 89 million hectolitres. The UK produces approximately 50% of the German output with 46 million hectolitres, followed by Poland with 38 million hectolitres and Italy with 13 million hectolitres.

Assuming an average power consumption of 10 kWh per hectolitre beer, large breweries reach significant power consumption. Figure 35 illustrates the estimated power consumption of large breweries and gives an indication of the required installed capacity to cover the corresponding power demand.

In total, breweries could account for more than 250 GW_{el} of distributed power capacities. Thus, installed capacity amounts to 126 MW_{el} in Germany, 57 MW_{el} in the UK, 19 MW_{el} in Italy, and 54 MW_{el} in Poland. The actually addressable market may be around 10% of that per year.

CHP biogas systems in wastewater treatment facilities

Wastewater treatment facilities are a highly attractive market for CHP due to their large potential to produce biogas through anaerobic digestion. However, this potential is largely untapped across Europe. There is increasing interest in harnessing the energy potential of wastewater treatment facilities and significant steps are expected to commence towards distributed energy production at European level. Currently, 4 TWh of electricity are produced annually from European wastewater treatment plants.

There are almost 10,000 wastewater treatment facilities in Germany, more than 8,000 in the UK, 7,600 in Italy and 3,000 in Poland. However, the share of these that have invested in anaerobic digestion infrastructure is insignificant.

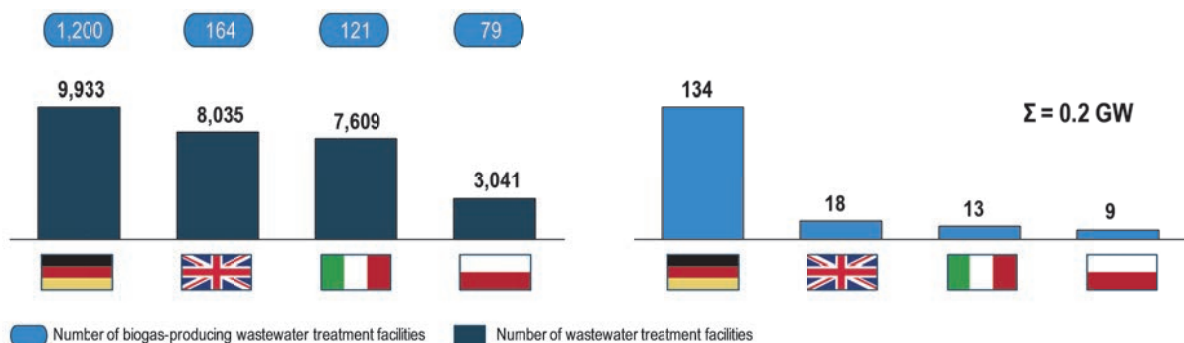


Figure 36: Wastewater treatment facilities, biogas-producing facilities and estimated installed capacities [MW_{el}]

Wastewater treatment facilities significantly differ in size, depending on population and industrial activity in their proximity. The business case for investing in anaerobic digestion infrastructure and CHP system must thus be calculated on a use-case basis. It is estimated that anaerobic digestion could be economically viable also for smaller wastewater treatment facilities of 10,000 population equivalent.

Taking into account only the wastewater treatment facilities that use anaerobic digestion to produce biogas and estimating an average biogas production of 800,000 m³ per facility, we estimate that currently there are installed capacities of almost 175 MW_{el} in the four focus markets. However, given the low penetration of anaerobic digestion, installed capacities could grow substantially. The actual addressable market may thus be 10% of the installed capacities plus the conversion share of facilities that do not use gas yet.

Key learnings from Chapter C

- The UK is the biggest primary market in the residential segment
- Poland has the greatest share of new builds in the primary and secondary market
- The gas market plays an important role in Italy, the UK and Germany in terms of the penetration of the gas grid in order to allow for stationary fuel cells to commercialise using existing infrastructure
- Germany and Poland display the highest growth rate for apartment buildings
- UK and German office and commercial buildings are the biggest market segments in the commercial segment
- The UK has the largest addressable market for data centres
- Germany has the biggest addressable market for chemical and pharmaceutical production facilities, breweries and wastewater treatment facilities

D. Review of stationary fuel cell systems and cost-down potential

The European landscape of stationary fuel cells for distributed generation has grown increasingly rich and diverse in terms of the solutions for different markets, segments and use cases that the industry can provide. Fuel cells can meet both fairly homogeneous customer requirements as in residential buildings, but also deliver tailor-made solutions for serving the energy needs of such special industrial applications as breweries or wastewater treatment plants. This chapter presents different types of stationary fuel cells for different market segments and use cases of distributed energy generation. It describes the current state of innovation and outlines future development potential in technical, economic and environmental terms.

For the time being, it appears that the European industry for stationary fuel cells is developing by and large independently from the commercialisation of fuel cells for transport applications (e.g. for fuel cell electric vehicles or fuel cell buses) given the partially different technology lines and different industry focus. However, there may be more synergies and spill-over in the supply chain in the future as both industries progress and commercialise their products.

Methodology: Defining generic fuel cell systems for analysis

At the core of this study is the evaluation of the technical, economic and ecological merits of stationary fuel cells – as the fundamental ingredient for benchmarking them with competing technologies. Conducting a comprehensive and rigorous benchmarking analysis requires a solid fact base of valid data across a number of performance dimensions. Most importantly, this includes detailed data on current and future costs (production, operation, maintenance, etc.), technical metrics (capacity, efficiency, lifetime, etc.) and emission factors (greenhouse gases, pollutants, particulates, noise).

Given the limited availability of academic literature on these features of stationary fuel cell systems, the study set out to gather the necessary fact base directly from industry members in the coalition thus using a unique first-hand data set from several dozens of players. Our data collection approach consisted of three steps: Defining required data points, collecting and aggregating data, as well as peer reviewing and approving data for analysis.

Defining required data points: Initially, all Working Groups agreed on different fuel cell technology clusters (e.g. a cluster of fuel cell mCHPs with up to 1 kW_{el} installed capacity for the residential market segment) for each of which they committed to supply data. Subsequently, the Working Groups defined, for each cluster, a distinct data collection template to characterise stationary fuel cells in the different use cases of the residential, commercial and industrial market segment. The templates comprised different categories for data points:

- **Technical data points** (e.g. electrical and thermal capacity, electrical and thermal efficiency, system design life and necessary stack exchanges, availability of the fuel cell, and the intended operating strategy),
- **Cost and/or price data points** (specifically initial system cost split up for different components, installation cost, maintenance cost),
- **Data points on emissions factors** (greenhouse gases, pollutants, particulates, noise) and finally
- **Data on physical characteristics** of the system (installation mode, size, volume, and weight).

For all stationary fuel cell systems in the scope, the cumulative production volume per company or the cumulative installed capacity per company is assumed to be the dominant driver for cost reduction (i.e. the learning-curve effect) and further technical improvement (e.g. increases in efficiency, availability, stack durability etc.). Time was considered as a secondary driver. Therefore, data points were collected for fuel cell systems at different stages of technology development, e.g. commonly agreed milestones for cumulative production volume or the cumulative installed capacity.

Collecting and aggregating data: The data collection and aggregation approach followed a clearly defined, transparent procedure. For all defined technology clusters, at least four and a maximum of eight coalition members supplied data in the pre-defined template so that a standard Roland Berger clean team approach for sanitising and aggregating technology data could be applied. Ultimately, the coalition jointly decided to define – based on the sanitised and aggregate data – one generic fuel cell per technology cluster with features of a hypothetically available product in the market. The generic fuel cells were derived along standard procedures of the clean team approach: The leading principle for the clean team was the determination of averages across all data points whilst acknowledging the specific standard deviation. In doing so, the clean team plotted all data points per category in order to identify, challenge and exclude extreme outliers as well as in order to examine cases of standard deviations significantly above average. Where necessary and appropriate, data averages were used to fill data gaps as well as relative ratios amongst materially related data points. Wherever two alternative, yet close data points for a generic fuel cell were conceivable, the clean team chose the relatively better value.

Before presenting the initial results of the clean team process to the coalition again, the clean team reviewed and challenged the data points using the limited literature and studies available. Furthermore, the clean team consulted independent academic and industry experts within the Roland Berger network to assess the data and perform plausibility checks.

Peer reviewing and approving data for analysis: Finally, the proposals for generic fuel cell systems per technology cluster were presented to the relevant working groups for discussion, validation, and final approval. Upon final approval of the consolidated, sanitised data sets by the relevant working groups, the data will be used as the basis for the analytical work in the subsequent benchmarking analysis

In summary, the overall result of the data collection and clean team process is hence a set of generic, technology-agnostic stationary fuel cell systems that enter as such into the benchmarking exercise with conventional technologies.

Technology clusters: Overview of clusters of stationary fuel cells

Stationary fuel cells have diversified substantially in terms of numerous dimensions, such as the underlying fuel cell technologies or the operating strategies in different use cases, e.g. power- or heat-driven operation of a fuel cell CHP unit. The most fundamental differences that translate into diverging performance and suitability for different use cases stem from different technology lines. Different technology types are made of different materials, feature different degrees of flexibility, require different types of fuel and operate at different temperature levels. They even vary to some extent in essential performance characteristics such as higher efficiencies or longer lifetimes – both in terms of current state of development as well as further potential for technical improvement. However, all have their right to exist and should be only considered as a means of serving varying use case characteristics.

For the purpose of analysing the wide array of different systems, we therefore defined a range of homogeneous clusters of fuel cells along different market segments and sub-segments. The clusters represent the most relevant categories of different stationary fuel cells from a demand-side perspective. For each of these clusters, we then defined a generic stationary fuel cell. The generic fuel cells and their

corresponding clusters primarily differ in terms of the electrical and thermal capacity of the fuel cell system and moreover meet different use-case requirements and prerequisites such as energy generation (CHP vs. base-load power) or fuel availability (natural gas, biogas, pure hydrogen etc.). There are six distinct technology clusters: fuel cell micro-CHPs (mCHPs) for the residential segment, fuel cell mini-CHPs and commercial fuel cell CHPs for the commercial segment, industrial prime power fuel cells, industrial fuel cell CHPs fuelled with natural gas and industrial fuel cell CHPs fuelled with biogas.

Residential	1 Micro-CHP	<ul style="list-style-type: none"> > Micro-CHP used in 1/2-family dwellings/single flats > Competition with 1/2-family dwelling/single flat heating/CHP solutions
Commercial	2 Mini-CHP	<ul style="list-style-type: none"> > Mini-CHP used in apartment buildings > Competition with central apartment building heating/CHP solutions
	3 CHP _{Commercial}	<ul style="list-style-type: none"> > CHP used in commercial buildings with capacity > 50 kW_{el} > Competition with commercial heating/CHP solutions > 50 kW_{el}
Industrial	4 Prime power	<ul style="list-style-type: none"> > Prime power large scale for data centres > 1 MW_{el} > Competition with grid and back-up
	5 CHP _{Natural gas}	<ul style="list-style-type: none"> > CHP for natural gas industrial applications ~ 1.4 MW_{el} > Competition with other CHP solutions
	6 CHP _{Biogas}	<ul style="list-style-type: none"> > CHP for biogas industrial applications ~ 0.4 MW_{el} > Competition with other CHP solutions

Figure 37: Generic stationary fuel cells within each market segment

Data points supplied by members of the coalition laid the foundation for the technology analysis. Based on the data and following the above outlined clean team approach, we defined generic fuel cell systems per technology clusters. For each technology cluster, at least 4 and up to 8 data sets were used to define the different generic fuel cells. The generic systems are realistic (albeit hypothetical) industry products, even though the market readiness of clusters differs.

Cluster 1: Fuel cell micro-CHP for 1/2-family dwellings (1 kW_{el})

One of the most mature clusters of stationary fuel cells comprises mCHPs to supply heat and electricity to residential 1/2-family dwellings, i.e. small family homes or single flats in apartment buildings. Whilst East Asian markets such as Japan and South Korea have already seen the beginning of the commercialisation of fuel cell mCHPs, numerous European manufacturers are now gradually bringing their mCHPs to the market – partially in cooperation with Japanese industry players. Currently, one group of European mCHP players is procuring complete PEM-based fuel-cell modules from Japan and integrating them into complete systems for the European markets. Another group focuses on development of European stacks (mostly SOFC technologies) – either in-house or from European suppliers. At this point in time, the former group's PEM-based mCHPs with Japanese components tend to be more mature and hence closer to commercial market penetration in Europe than the latter group of European SOFC systems, which are expected to catch up over the next 2-3 years.

All mCHP systems are typically highly standardised products with mass-market orientation. A fully packaged fuel cell mCHP heating solution for 1/2-family dwellings typically features the following components:⁶³

⁶³ Cf. Imperial College Business School (2012), IFEU (2012)

- A stack of fuel cells that uses hydrogen to generate heat and electricity
- Added system components:
 - A fuel processing unit that reforms any hydrocarbon (natural gas, biogas etc.) to hydrogen and carbon dioxide
 - A grid-tie inverter to convert low-voltage direct current to standard alternating current (230 V)
 - A heat exchanger to transmit waste heat in the fuel cell module to an external heating system
 - Balance of Plant (BOP)
- Additional thermal management:
 - An auxiliary state-of-the-art condensing boiler to meet peak heat demands
 - A high-efficiency combined heat store for storage of heating water as well as hot drinking water (buffer storage)
- Control, sensors and feedback (e.g. smart meter)

In physical terms, the whole system is either designed to replace a floor-based (for homes with dedicated cellars) or a wall-mounted gas boiler system whilst only requiring slightly more volume due to the combination of boiler and fuel cell module.

A typical fuel cell mCHP with 1 kW_{el} and 1.45 kW_{th} is likely to have the technical features as shown in Figure 38 – with estimated system cost that significantly drop with increasing production volumes:

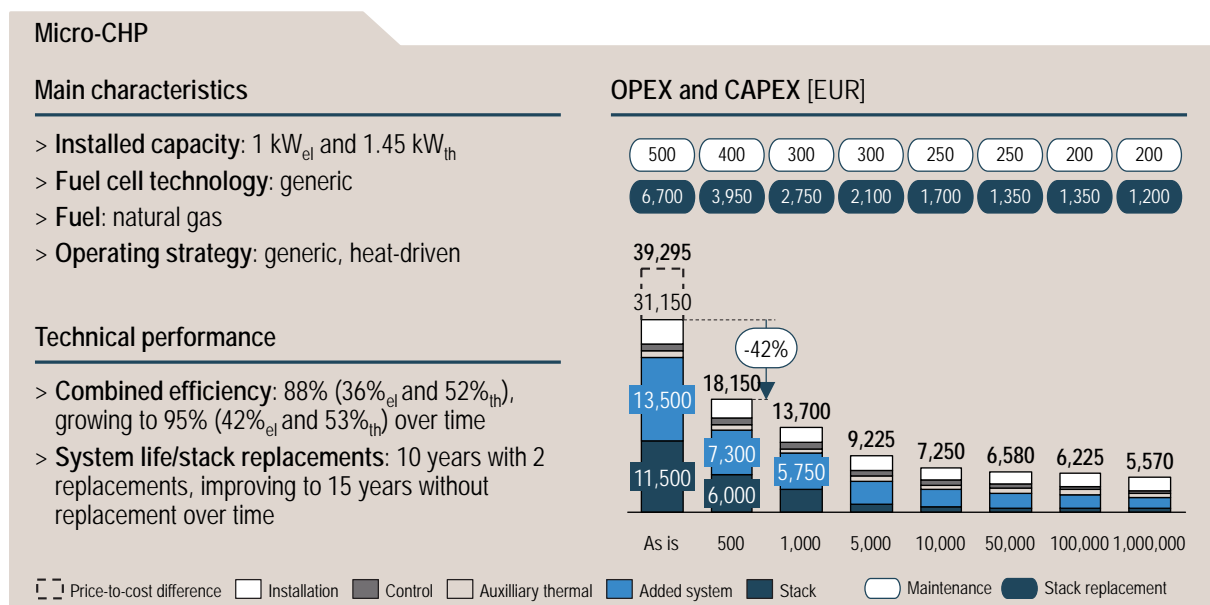


Figure 38: Technology and cost profile of generic fuel cell integrated mCHP⁶⁴

Technical features

Capacity: The generic fuel cell has an electrical capacity of 1 kW_{el} – approximately the average of the industry range that currently offers capacities between 0.3 and 1.5 kW_{el} for use in 1/2-family dwellings. The thermal capacity is 1.45 kW_{th}. The auxiliary state-of-the-art condensing boiler is a standardised

⁶⁴ Price figures excluding VAT (assuming constant OEM & wholesale margin at 30%), cumulative production volume per company

product (e.g. with a capacity of 13 kW_{th}) that covers the peak heat demands to cover a building's maximum heat load effectively.

Technology: As outlined above, the generic fuel cell is deliberately kept technology-agnostic. Dominant technologies in the industry are low-temperature and high temperature polymer electrolyte fuel cells (PEMFC) and solid oxide (SOFC) fuel cells – each of which has its distinct set of strengths and weaknesses, regarding flexibility, electrical efficiency, etc.

Fuel: Like virtually all fuel cell mCHPs, the generic system builds on existing heating fuel infrastructure and uses natural gas. Alternatively, many fuel cell mCHPs can also run on pure hydrogen and biogas – the latter of which would eliminate the need for reforming and provide a heating solution with zero emissions.

Operating strategy: The vast majority of all industry players in general and the OEMs of integrated fuel cell mCHP in particular aim to operate the fuel cell mCHP along the heat demand of the 1/2-family dwelling in question, i.e. pursue a heat-driven strategy with electricity as an "add-on" product from cogeneration. In Europe, fuel cell mCHPs are heating solutions first and power generation systems second – unlike in Japan where fuel cell mCHPs are banned from feeding excess power into the grid and hence operate in a power-driven mode with heat as the by-product.⁶⁵ In Europe, products differ considerably when it comes to more specific questions of operation such as start-stop cycles and operating hours – differences that are partially dependent on the technology in place. For example, some players start the fuel cell CHP once at the beginning of the heating season and do not shut it down until the end whilst others start and stop at least once every day. For the purpose of the analysis with the generic fuel cell above, we thus consider a generic fuel cell with a heat-driven operating strategy that modulates its used capacity to some extent – however only insofar as it does not reduce its efficiency. It is directed towards supplying the basic heat demand of the dwelling, whereas the auxiliary condensing boiler covers demand peaks beyond the fuel cell's thermal capacity. In order to maximise operating hours (and hence cogeneration) of the fuel cell mCHP, a combined buffer storage is installed as part of the set-up or the existing one is used.

Efficiency: The thermal and electrical efficiency of the fuel cell mCHP depends both on the technology choice of manufacturers as well as general preferences for either particularly heat- or power-efficient generation. The average, generic fuel cell has an electrical efficiency of 36%_{el} and a thermal efficiency of 52%_{th} that is expected to grow further – particularly on the electrical side – with additional technology improvement to 42%_{el} and 53%_{th} respectively. Manufacturers have even reached electrical efficiencies of 60%_{el} and more (at lower thermal efficiencies) or in other cases increased thermal efficiency to as much as 58%_{th}. In any case, the industry considers combined efficiencies of well beyond 90% within reach. For our analysis, we use the average, generic fuel cell. Completing the overall efficiency assessment of the fully packaged system, the auxiliary state-of-the-art condensing boiler has a thermal gross efficiency of up to 109%; however, actual net efficiencies tend to be approximately 95%.

System life and stack replacements: Depending on the maturity and experience of different technologies and manufacturers with operations of fuel cell mCHPs, current system lifetimes in the market vary somewhat – especially because the durability of different fuel cell stacks differs. On average, current industry data indicates a system design life of 10 years whilst requiring two replacements of the stack during that period. The industry expects to improve both system life and stack lifetime as the technology matures, eventually reaching – on average – 15 years without replacement. We consider these characteristics for the generic fuel cell in our further analysis. Some upsides even

⁶⁵ However, some European players focus on power-driven, fuel cell mCHPs as add-on solutions that by and large run continuously in base-load mode irrespective of the heat demand of the building in question. Unlike in Japan, these units feed excess electricity into the grid

predict 20-25 years of system life, with no more than one stack replacement. Industry representatives stress that the further increase of stack durability and system life remains a critical area for further technology development that is less driven by growing production volumes but rather by more time and resources for product development as such.

Apart from growing volumes to yield learning effects and drive down costs per unit, the European stationary fuel cell players (and especially the developers of less mature SOFC-based mCHPs) emphasise the need to advance the technology as such through further innovation. Particularly critical and equally challenging is the technological progress regarding:

- Reducing degradation of the cell, i.e. the gradual reduction in capacity and efficiency, with higher process capacity and narrower variation of cell performance to increase the lifetime of the fuel cell stack (initially beyond 20,000 operating hours, later beyond 40,000 and even 80,000 operating hours) to eventually eliminate stack exchanges over the system design life
- Increasing the robustness of the stack design that can withstand critical situations (emergency shutdown etc.) to eliminate risk of stack failure through external factors
- Increasing electrical efficiency to account for increasing heat demand and decreasing electrical demand in the building sector
- Design to cost and design for manufacture and assembly both within stack production and in terms of system integration

Economic characteristics

Cost of system (CAPEX): Current system costs differ to some extent amongst different technology types and manufacturers – mainly due to the different degrees of maturity that fuel cell mCHPs have reached until now. Currently, a mCHP system can be produced by industry OEMs at a cost of – on average – approximately 34,000 EUR per kW_{el} installed. The standard deviation for this cost position in the sample was 30%. The cost of system is vastly driven by the fuel cell module that makes up approximately 90% of all cost on the manufacturer's end. The stack and added-system cost make up 54% and 46% of the cost of the fuel cell module, respectively, when considering a generic fuel cell. Installation currently adds another 15%. When additionally considering typical OEM and trade margins – here we assume 30% in total – as well as average anticipated installation costs, an estimated end-customer price (excl. VAT) adds up to more than 39,000 EUR (excl. VAT) for the 1 kW_{el} generic fuel cell system that we consider as a representative product for the residential segment. That is 8-10 times the price of a state-of-the-art condensing boiler to heat a 1/2-family dwelling, depending on the geographic market. This hypothetical end-customer price does not consider any investment subsidies, tax credits or other policy support.

The mCHP industry expects system costs to drop significantly, once companies' production volumes increase to small-series and eventually fully industrialised production. Industry members believe that substantial learning effects are possible. The further production volumes increase, the stronger the expected system cost per kW_{el} is likely to align amongst manufacturers within the technology cluster of fuel cell mCHPs – given our analysis of the first-hand industry data that we collected for this study where we requested manufacturers to predict and justify their individual learning curve. The industry anticipates three major phases of the technology learning curve with corresponding cost degeneration.

Standardisation (up to 500 units cumulative production per company): The first significant cost reduction step is expected to be achievable when companies reach the milestone of 500 units cumulative production. On average, the industry players expect total system cost to drop by some 40% (excluding manufacturer and trade margin, but including installation cost). Cost reduction is expected to come both from stack production and added system components. With regard to stack production, the following levers will lower costs per unit – particularly for SOFC mCHPs: increasing batch sizes to

reduce set-up time ratios, direct labour costs and energy use; improving process capability in cleaning, spraying and firing to reduce scrap rate; adopting basic automation of manually-intensive processes; achieving higher equipment and material utilisation; implementing simple lean organisation of process steps and work flow optimisation. In terms of added system, the cost degression drivers are: increasing the sourcing of fuel-cell specific BoP components; developing special low-volume tooling; transitioning suppliers from prototype workshops to commercial pilot and small volume lines as well as the simplification of quality control. Currently in the progress of completing this standardisation phase, some European system developers who have commenced commercialisation have already achieved cost reductions of approximately 25%.

Industrialisation (up to 10,000 units cumulative production per company): The second important milestone is the mark of 10,000 units cumulative production per company where system cost are expected to decrease by a further 60% down to then 7,250 EUR (incl. installation costs). The anticipated cost degression is expected to come primarily from the stack, closely followed by added system costs whilst installation and the cost of auxiliary thermal management are expected to remain fairly constant. Primary reasons for this further cost reduction are on the stack side: semi-automation of the production and assembly process especially removing costly and repetitive manual handling through replacement with automatic loading cartridges; more competitive sourcing of components and materials starting in this volume range; reduction in takt time via higher speed lines; larger batch sizes – especially for energy-intensive processes (such as firing for high-temperature SOFCs). On the part of the added system, cost degression is expected to come from: automation and serial tooling of manufacturing with regard to bespoke items (e.g. heat exchanger and hot-box metal work), transition from special to standard specification parts (e.g. for pumps and sensors), standardisation of component designs and thus gradually growing the supplier base, competitive sourcing of (semi-)standard components, semi-automated end of line testing for BoP and CHP assemblies. The SOFC industry expects at this stage to implement manufacturing processes that mirror those for thermal components in the automotive industry or truck platforms as volumes are similar.

Mass-market production (beyond 10,000 units cumulative production per company): Ultimately, in the range of 1,000,000 units cumulative production per company, system costs may even decrease to less than 5,600 EUR (incl. installation costs). Installation costs are expected to remain relatively constant and thus eventually make up between 30% and 40% of total system cost (when excluding manufacturer and trade margins). In this volume range, the stack producers expect to move from batch production to completely automatic manufacturing lines with removal of all but essential manual handling whilst aiming for single-piece process flows to increase Overall Equipment Effectiveness and further reduce set-up times. Moreover, improved and new production methods (such as high-speed metal forming for steel elements) and design-for-manufacturing processes are expected to drive down stack costs. With regard to the added system within the fuel cell mCHP, system developers see significant levers for further cost reduction under mass-market production: automated manufacturing and tooling with high dedicated lines; full transition to tiered sub-system of suppliers; implementation of low-cost BoP designs suitable for high-volume manufacturing; all-out competitive sourcing and potential outsourcing of suppliers and even manufacturing to low-cost countries (particularly for labour-intensive components such as brazed hot-box components in SOFC systems); fully automated end of line testing.

Overall, we deem the increasingly competitive sourcing of materials beyond lab-quantity suppliers to have the most significant impact on stack production costs. In terms of added system components, growing volumes may attract a wider choice of suppliers who are looking for growth and diversification (e.g. away from lower margin and vulnerable automotive, consumer electronics sectors). Increased supplier choice will help drive down BOP costs as the development of fully capable sub-system tier suppliers will be a critical enabler.

Maintenance cost (OPEX) and cost of stack replacement: During the lifetime of the fuel cell mCHP the system has to be maintained regularly – for which the customer incurs a cost. Moreover, as outlined above, the stack may have to be replaced during the system life which essentially means a re-investment in the technology that the customer has to undertake.

Maintenance cost: mCHP manufacturers on average currently estimate annual maintenance cost for the customer of 500 EUR (excl. VAT). With increasing production volumes and experience gains for manufacturer and installers alike, maintenance costs will decrease by as much as 60% to 200 EUR p.a. (excl. VAT) and thus eventually be in the range of annual maintenance cost for boilers – and well below other, engine-based CHP technologies. Learning effects will drive down maintenance costs as less time is needed for diagnostics, processes become routine and installers gradually reduce risk premiums associated with new technologies.

Cost of stack replacement: The cost of stack replacement for the generic fuel cell system of 1 kW_{el} yields currently 6,700 EUR per stack (incl. installation, excl. VAT) for the customer. Replacement stacks will benefit earlier from volume-driven degression of stack costs, provided that newer, cheaper stacks are compatible with older systems. Based on the industry data collected, the cost of the generic fuel cell's replacement stack is expected to fall by more than 50% by the time the cumulative production per company passes the threshold of 1,000 units – eventually dropping to 1,200 EUR under mass-market production.

Cluster 2: Fuel cell mini-CHP for apartment buildings (5 kW_{el})

Completing the portfolio of stationary fuel cells in residential use cases, mini-CHP systems with an installed capacity of up to 5 kW_{el} can supply typical apartment buildings with base-load heat – in a combined system with one or several auxiliary condensing boilers.

As for mCHPs in smaller residential buildings, a connection to the gas grid and a central warm-water supply throughout the entire building are essential prerequisites for the installation of fuel cell mini-CHPs in apartment buildings – otherwise, the customer has to incur additional switching costs. Moreover, the structural set-up of the fully packaged fuel cell mCHP solution is similar to mCHPs for 1/2-family dwellings as it features both a fuel cell module with the stack and added system as well as additional thermal management – including most importantly one or more auxiliary condensing boilers to supply the peak heat demand of the apartment building. As such, the industry expects to supply apartment buildings of varying size and insulation with – by and large – standard products (e.g. with a capacity of 5 kW_{el}) and cover the residual heat demand with condensing boilers in different numbers and sizes depending on the building requirements.

Unlike in the case of mCHPs for 1/2-family dwellings, the fuel cell industry has not yet supplied a significant number of products to the market segment of apartment buildings – neither in Europe, nor elsewhere. Products are still predominantly in the prototype and small-field-test phase. Moreover, stack suppliers are in the process of partnering with system integrators, engineering consultants and other market players to offer fully fledged solutions for real estate developers. Overall, the market segment is in a comparatively young stage. Consequently, the foremost priority for stack producers and system developers envisioning stationary fuel cells for commercial buildings in a medium power range is to deliver successful demonstration projects and larger field tests to showcase the readiness of the technology.

Considering the forecasts of several fuel cell suppliers that pursue the market segment of apartment buildings, a typical fuel cell mini-CHP with 5 kW_{el} and kW_{th} is expected to have the following technical features as shown in Figure 39 – with estimated system cost that significantly drop with increasing production volumes:

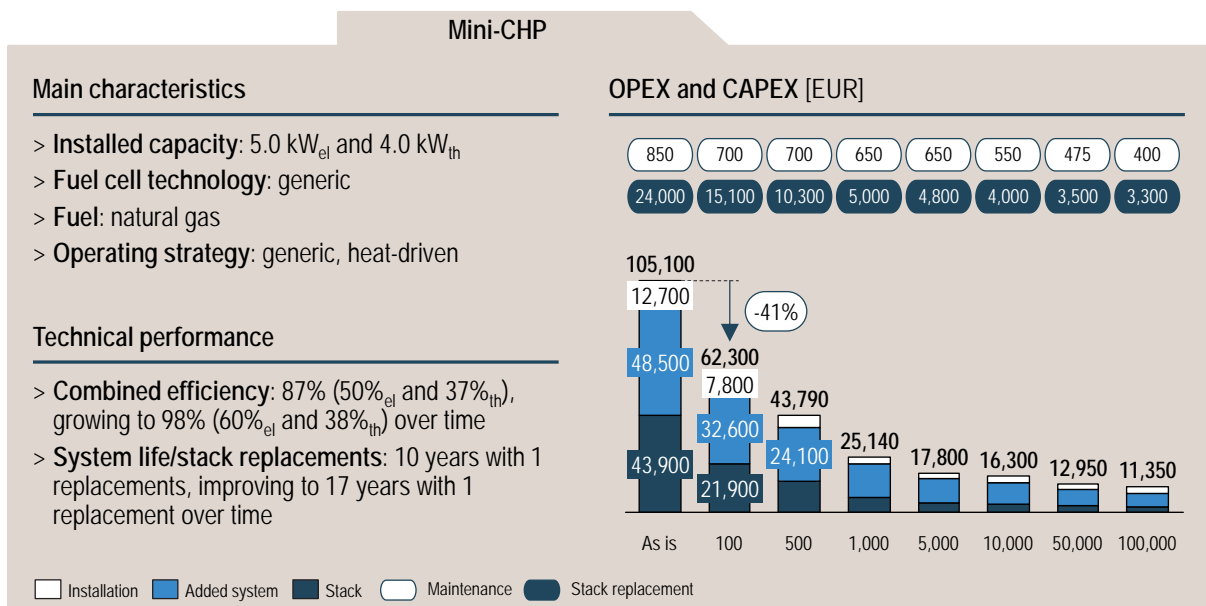


Figure 39: Technology and cost profile of generic fuel cell mini-CHP⁶⁶

Technical features

Capacity: The generic fuel cell has an electrical capacity of 5 kW_{el}; the thermal capacity is 4 kW_{th}. The auxiliary state-of-the-art condensing boilers are standardised products (e.g. a capacity of 13-50 kW_{th}) that cover the peak heat demands up to the apartment building's maximum heat load.

Technology and fuel: As outlined above, the generic fuel cell is deliberately kept technology-agnostic. However, fuel cell suppliers that pursue the market segment predominantly focus on SOFC technologies for mini-CHP solutions. Like virtually all fuel cell mini-CHPs, the generic system builds on existing heating fuel infrastructure and uses natural gas.

Operating strategy: Given the lack of practical, in-field experience with fuel cell mini-CHPs around 5 kW_{el}, we refrain from discussing best practices for operating strategies at this stage. Fuel cell suppliers mainly aim to run the fuel cell unit as determined by the heat demand of the apartment building in question. The combined buffer storage that is installed as part of the set-up has the same role as in 1/2-family dwellings. Fuel cell suppliers indicate that the operating strategy may evolve over time and flexibly follow both heat and electricity demand.

Efficiency: The thermal and electrical efficiency of the fuel cell mini-CHP are technology-driven and also determined by the general preferences for any operating strategy. If currently installed, the average, generic fuel cell would have an electrical efficiency of 50%_{el} and a thermal efficiency of 37%_{th} that is expected to grow – particularly on the electrical side – with additional technology improvement to 60%_{el} and 38%_{th} respectively. Some manufacturers expect to even reach electrical efficiencies of up to 63%_{el} (at lower thermal efficiencies). In any case, the industry considers combined efficiencies of well beyond 95% realistic.

System life and stack replacements: Given that manufacturers of mini-CHP with up to 10 kW_{el} mainly rely on prototype testing and have limited in-field experience, current systems vary because the durability of different fuel cell stacks differs. On average, current industry data indicates a system design

⁶⁶ CAPEX excluding additional thermal management; cost figures except for installation, maintenance and stack replacement. Production volume is cumulative and per company

life of 10 years whilst requiring one replacement of the stack during that period. The industry expects to improve both system life and stack lifetime as the technology matures, eventually reaching – on average – 17 years without replacement. Some optimistic accounts even predict 20 years of system life, with one stack replacement.

According to industry players in the commercial segment (especially stack producers), the most critical technical advances – irrespective of learning effects from growing volumes are:

- Increasing the lifetime of stacks by lowering degradation rates
- Improving the robustness of the fuel cell module to eliminate the risks of stack failure through external shocks such as emergency shut downs
- Raising efficiency (especially electrical) to higher levels

Economic characteristics

Cost of system (CAPEX): The cost projections for a generic 5 kW_{el} fuel cell mini-CHP system differ slightly depending on different technologies, but vary less than mCHP figures as the technology is at a homogeneously less mature stage of development. According to the industry data supplied for this technology cluster, a 5 kW_{el} CHP system could be delivered by fuel cell suppliers at a cost of approximately 92,400 EUR, i.e. 18,400 EUR per kW_{el} installed. These figures do not include any cost of necessary additional thermal management to cover the peak heat demand of the building as well as the cost of installation. The standard deviation for the current cost position of the fuel cell system in the sample was 30% with regard to the system cost per kW_{el}. The cost of the fuel cell module is equally driven by the stack and added-system cost that contribute 48% and 52% respectively when considering the generic 5 kW_{el} fuel cell. Installation costs have to be estimated given the lack of practical experience with the operationalisation of stationary fuel cells in this segment. When considering comparable installation costs for engine-based CHPs, the novelty of the fuel cell technology as well as the initial cost of system, we anticipate initial installation costs between 12,000 EUR and 13,000 EUR for the generic 5 kW_{el} fuel cell module (approximately 14% of the fuel cell module cost). Fuel cell suppliers for the apartment segment expect system costs to drop significantly as they believe that substantial learning effects are possible. The industry anticipates the following major steps and phases in the technology learning curve and resulting cost degression:

Initial roll-out (up to 100 units cumulative production per company): Reaching a cumulative total production level of 100 units per company and thereby entering small-series production, system costs (excluding additional thermal management, but including installation) are projected to fall by nearly 60% to 62,300 EUR per system (54,500 EUR excl. installation). The main reasons for this cost reduction are production process stabilisations, the increase of process yields, and the elimination of expensive "lab-scale" processes for the stack production. In terms of added system, overhead reduction for standard metal sourcing is anticipated to generate substantial savings.

Standardisation (up to 5,000 units cumulative production per company): The second important milestone is the mark of 5,000 units cumulative production per company where system costs are expected to decrease by a further 70% down to then 17,800 EUR (incl. installation costs, excl. additional thermal management). The anticipated cost degression is expected to come both from the reduction in stack costs as well as costs of added system (e.g. heat exchanger, reformer). Installation costs are also projected to fall indicating some learning effects in the operationalisation of fuel cell mini-CHPs on site. According to suppliers participating in the study, the primary reasons for this significant further cost reduction will come from stack production advances, specifically the improved utilisation of existing manufacturing equipment and workforce, the automation of selected process steps, and the low volume outsourcing of standardised components. In terms of added system, competitive sourcing of

components (e.g. BoP, heat exchangers, grid-tie inverters) and design standardisation bear great cost reduction potential.

Industrialisation (beyond 5,000 units cumulative production per company): Ultimately, in the range of 100,000 units cumulative production per company, system costs may even decrease to less than 11,350 EUR (incl. installation costs, but excl. additional thermal management).

Fixed maintenance cost (OPEX) and cost of stack replacement

Fixed maintenance cost: Potential fuel cell mini-CHP suppliers currently estimate average annual maintenance cost for the customer of 850 EUR (excl. VAT) per system. With growing experience and competition amongst installers and service providers, this is projected to decrease by more than half to 400 EUR p.a. (excl. VAT) – and well below other, engine-based CHP technologies that are already installed in apartment buildings today and tend to be comparatively maintenance-intensive.

Cost of stack replacement: Replacing the stack of the generic 5 kW_{el} fuel cell mini-CHP can currently be projected to cost approximately 24,000 EUR (incl. installation, excl. VAT) for the customer. Replacement stacks will benefit earlier from volume-driven degeneration of stack costs, provided that newer stacks are compatible with older systems. Based on the industry data collected, the cost of stack replacement is expected to fall by more than 50% once the cumulative production per company passes the threshold of 500 units.

Cluster 3: Fuel cell CHP for commercial buildings (>50 kW_{el})

A further relevant technology cluster for fuel cell CHP solutions concerns medium-size CHP systems to supply commercial buildings such as office buildings, retail centres, hotels or hospitals with heat and power. Industry players eyeing this segment are by and large the same ones that target apartment buildings. As with the 5 kW_{el} apartment solutions, the European industry is at a considerably earlier stage of development than the fuel cell mCHP manufacturers. Larger-scale field tests have not yet commenced. Products are still predominantly in the prototype and small-field-test phase. Moreover, fuel cell module suppliers are in the process of identifying prototype projects and only beginning to approach system developers, engineering consultants and other market players to offer fully fledged solutions to commercial developers.

Buildings in this cluster typically require CHP solutions with installed electrical capacities of 50 kW or more. The different types and even different buildings within the same type tend to vary substantially in terms of size, insulation, commercial use and other factors determining heat and power demand – more so than residential buildings. Consequently, the fuel cell CHP solutions that are currently being pursued and prototyped by the industry are to a large extent customised, tailor-made solutions that use the modularity of the fuel cell technology to provide the right capacity for heat and power generation to the specific building. In general, the buildings that are part of the addressable commercial market for medium-size fuel cell CHPs need to be connected to the gas grid and have a central heating and warm-water supply system.

The generic fuel cell system for commercial buildings that we analyse in this study has an electric capacity of 50 kW_{el} and a thermal capacity of 40 kW_{th}. Principally, it is scalable upwards and downwards depending on the building requirements of a given use case. Figure 40 gives an overview of the main features.

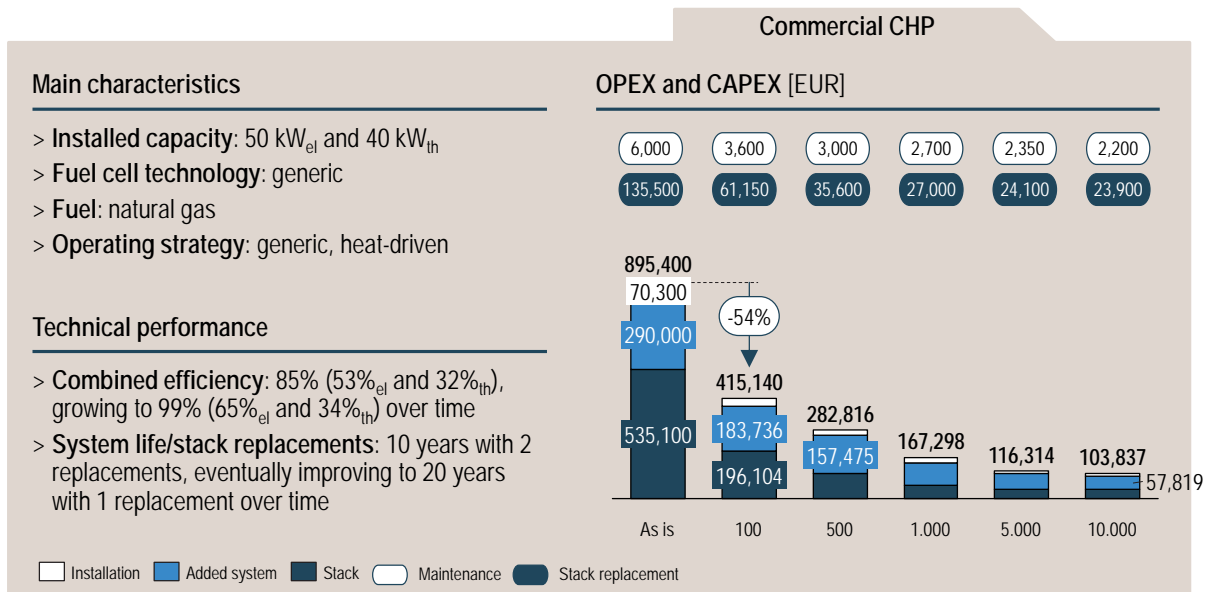


Figure 40: Technology and cost profile of generic fuel cell commercial CHP⁶⁷

Technical features

Capacity: The generic fuel cell system for commercial buildings that we analyse in this study has an electric capacity of 50 kW_{el} and a thermal capacity of 40 kW_{th}.

Technology and fuel: The generic fuel cell is purposely defined as using a generic fuel cell technology. However, the fuel cell suppliers pursuing base-load cogeneration solutions for commercial buildings tend to focus on SOFC technologies for commercialisation in the near future. The 50 kW_{el} generic fuel cell can run on natural gas, biogas or pure hydrogen – with natural gas likely to be the most common fuel.

Operating strategy: As there is little experience with actual operating strategies in real commercial buildings, fuel cell suppliers envision a primarily heat-driven strategy, but could also change to flexible base load, following the building's power demand. For the purpose of the analysis and the benchmarking in the following chapter, the generic fuel cell operates under a heat-driven strategy.

Efficiency: The current efficiency of a generic fuel cell in this technology cluster averages 53%_{el} and 32%_{th}, with further improvement potential up to a total efficiency of 99% (with 65%_{el} and 34%_{th}) through further research and development as well as growing production volumes.

System life and stack replacements: The generic fuel cell CHP for commercial buildings currently requires two stack replacements over a total system life of ten years. The industry expects to further improve the durability of the stack as well as the overall system life so that, eventually, a generic commercial CHP system could have a system life of as much as 20 years requiring only 1 stack exchange.

⁶⁷ CAPEX excluding additional thermal management; cost figures except for installation, maintenance and stack replacement. Production volume is cumulative and per company

Economic characteristics

Cost of system (CAPEX): Based on industry data collected, we estimate a generic fuel cell CHP with 50 kW_{el} for commercial buildings to cost the manufacturer 895,400 EUR (including installation, but excluding any additional thermal management such as tanks or condensing boilers), with system cost per kW_{el} at around 16,500 EUR (excluding installation or any additional thermal management). End prices will evidently be even higher, once the fuel cell CHP is complemented by any auxiliary boilers and manufacturer as well as possibly trade margin are added. The standard deviation for the current cost position of the fuel cell system in the sample was in similar ranges as for the mini-CHP with regard to the system cost per kW_{el}. The cost of the fuel cell module is mainly driven by the stack (65%) and less so by the added-system cost (35%) when considering the generic 50 kW_{el} fuel cell. Installation costs have to be estimated given the lack of practical experience. Considering comparable installation costs for engine-based CHPs, the novelty of the fuel cell technology as well as the initial system cost, we anticipate initial installation costs of around 70,000 EUR for the generic 50 kW_{el} fuel cell.

System costs are expected to drop significantly as substantial learning effects are possible, with the following major steps and phases in the technology learning curve and resulting cost degeneration. In general, the cost-down levers are similar to the 5 kW_{el} system above as the SOFC developers by and large pursue scalable systems. However, due to economies of scale, the learning rate and hence the relative cost degeneration is expected to be even higher.

Fixed maintenance cost (OPEX) and cost of stack replacement:

Fixed maintenance cost: Maintenance costs are expected to fall from ca. 6,000 to 2,200 EUR over the learning curve of the generic 50 kW_{el} fuel cell.

Cost of stack replacement: The cost of stack replacement is projected to drop from 135,500 to 61,150 EUR when manufacturers reach the threshold of 100 units cumulative production. Eventually, stack replacement may cost the customer no more than 24,000 EUR for the generic 50 kW_{el} fuel cell system.

Cluster 4: Fuel cell prime power for industrial applications (1,000 kW_{el})

The fuel cell prime power solution for data centres is considered to be one of the most promising use cases for stationary applications amongst all industrial applications. In the U.S., for instance, major companies have started to install fuel cell based prime power systems to supply their large corporate data centres (e.g. Apple, eBay, Microsoft, etc.). Further development is expected as companies such as Microsoft develop distributed rack and server-level power supply solutions for data centres, thus bypassing the expensive power transmission infrastructure and associated power losses.⁶⁸ Fuel cell systems can eliminate the need for UPS and back-up diesel generators by using the power grid as sole back-up, whereby maximum reliability is achieved.

In Europe, Equinix is testing a 100 kW_{el} fuel cell prime power system in Frankfurt. The system is also designed to provide fire suppression by managing the oxygen level in the room. This is possible as fuel cells can generate low oxygen concentration air as a by-product.

The data centre use case is first and foremost a power-driven case. Given the current fluctuation of power demand in data centres (between approximately 70-100%) and the expected increased fluctuation (to approximately 30-100%), the generic fuel cell system generated is largely focused on

⁶⁸ For more information, please refer to Box 3 on power security

electrical efficiency. Thus, the system is based on low-temperature fuel cells which enables load following operation.

High-temperature heat which could be provided by high-temperature fuel cells could be used for the cooling of data centres. However, the overall cooling trend in data centres is towards water cooling, which is significantly more effective than air cooling. IBM has developed a warm water cooling concept whilst Google sites a major data centre next to the Baltic Sea in Finland, where the cooling system mainly uses the cold seawater. The effectiveness of the system bypasses the necessity for chillers.

The fuel cell system dedicated to data centres as presented here can be applied to other use cases where the generation of heat is not obligatory and in which power security is crucial.

A fully packaged fuel cell prime power system for data centres typically features the following components:

- A stack of fuel cells that uses hydrogen to generate power and heat as a by-product
- Added system components to complete the fuel cell module, namely:
 - A fuel processing unit that reforms any hydrocarbon (natural gas, biogas etc.) to hydrogen and carbon dioxide
 - A grid-tie inverter to convert low-voltage direct current to standard alternating current
 - Balance of Plant (BOP)
- Control, interaction and feedback (e.g. smart meter)

A typical fuel cell prime power system with 1,000 kW_{el} is likely to have the following technical features as shown in Figure 41:

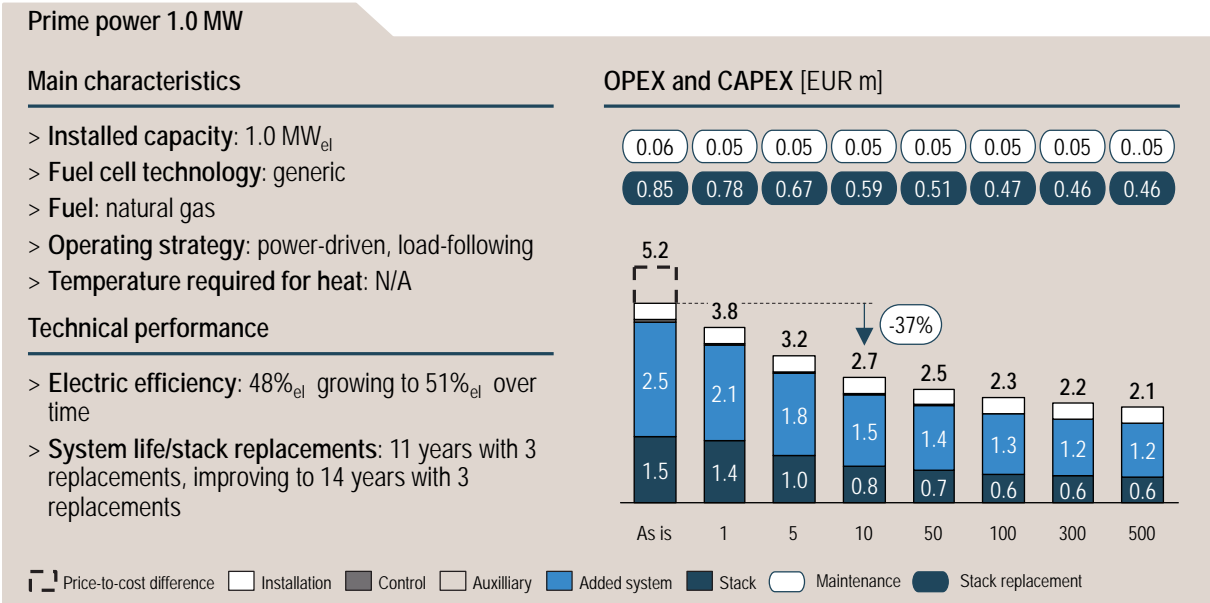


Figure 41: Technology and cost profile of generic fuel cell prime power⁶⁹

⁶⁹ Cost figures except for installation, maintenance and stack replacement . Volumes reference cumulative production volumes per company

Technical features

Capacity: The generic fuel cell has an electrical capacity of 1,000 kW_{el}.

Technology: The generic fuel cell is deliberately kept technology-agnostic. Dominant technologies in the industry are low-temperature polymer electrolyte fuel cells (PEMFC) and solid oxide fuel cells (SOFC).

Fuel: The generic system builds on existing fuel infrastructure and uses natural gas. Alternatively, fuel cell systems can also run on pure biogas and hydrogen (thus reaching zero emissions).

Operating strategy: The generic prime power fuel cell pursues load-following operation. The fuel cell system can thus adapt its power output to the demand of the data centre. The possibility to perform load following is highly dependent on the fuel cell technology used. High temperature fuel cells require a long run-up time and are rather rigid when adjustment of power output is required. High-temperature fuel cells can alternatively follow a base-load operation strategy and address peaks by using grid power. In this case, however, costs associated with back-up systems for the grid would also occur, whilst high-temperature heat is gained in the process.

Efficiency: The generic fuel cell defined has an electrical efficiency of 48%_{el}. The electrical efficiency can reach 51%_{el} following technology improvements. Several manufacturers expect to even reach electrical efficiencies of up to 60%_{el}.

System life and stack replacements: On average, current industry data indicates a system design life of 11 years whilst requiring three replacements of the stack during that period. The industry expects to improve both system life and stack lifetime as the technology matures, eventually reaching – on average – 14 years with the same number of replacements. Some upsides even predict up to 19 years of system life, with three stack replacements. Stack durability and system life remain critical areas for further technology development driven by increased R&D efforts.

Several technological improvements are achievable for the prime power system, which require further innovation and R&D efforts. These improvements are particularly relevant for the PEM and SOFC systems which are at incipient development levels. The most critical technological advances are:

- Increasing the electrical efficiency of the system to reduce end-user operating costs
- Reducing the degradation of the fuel cell, with narrower variation of cell performance to increase the lifetime of the fuel cell stack
- Improving power electronics and controls design to achieve significant cost reduction
- BOP standardisation to achieve costs savings on the one hand and reduce delivery times on the other hand
- Increasing cell power density and achieving thinner layers at cell level to reduce system volume and costs
- Substituting expensive materials (such as stainless steel) with alternative materials to reduce costs

Economic characteristics

Cost of system (CAPEX): Current system costs differ to some extent amongst different technology types and manufacturers. Currently, a 1 MW_{el} prime power system costs approximately 4,360,000 EUR. The standard deviation for this cost position in the sample is 10%. The cost of system is currently dominated by the reformer necessary to obtain hydrogen from natural gas which accounts for almost 50% of the costs. The stack makes up 37% of the fuel cell module. Installation currently adds another 8%. When additionally considering typical OEM and trade margins – here we assume 20% in total – as well as average anticipated installation costs the estimated end-customer price (excl. VAT) adds up to

more than 5,200,000 EUR (excl. VAT). This hypothetical end-customer price does not consider any investment subsidies, tax credits or other policy support.

Industry players expect system costs to drop significantly, once companies' production volumes increase to standardisation and eventually fully industrialised production. The industry anticipates the following major steps and phases in the technology learning curve and resulting cost degression:

Initial roll-out (up to 5 MW_{el} cumulative installed capacity per company): The first significant cost reduction step is expected to be achievable when companies reach the milestone of 5 MW_{el} cumulative installed capacities. On average, the industry players expect total system costs to drop by more than 25% (excluding manufacturer and trade margin, but including installation cost). For the fuel cell stack, the main reasons for cost reduction are the implementation of semi-automated stacking, a higher degree of integration of components (e.g. sensors integrated in end-plate) and increased batch sizes. The added system costs can be decreased by reducing connection piping and increasing manufacturing batch sizes especially for the metalwork of the heat exchanger and the reformer.

Standardisation (up to 50 MW_{el} cumulative installed capacity per company): The second important milestone is the 50 MW_{el} cumulative installed capacity mark per company where system costs are expected to decrease by an additional 23%, to 2,490,000 EUR (incl. installation costs). The anticipated cost reduction is expected to come primarily from the stack, closely followed by added system costs (mainly reformer) whilst installation cost is expected to remain fairly constant. The fuel cell stack can improve cost performance through fully automated stacking and automating manual handling for printing, firing and inspection. Added system costs can be reduced by reducing the number of sensors and adopting automated processes for thermal components.

Industrialisation (beyond 50 MW_{el} installed capacity per company): Ultimately, in the range of 50 MW_{el} cumulative installed capacities per company, system costs may even decrease to 1,700,000 EUR (incl. installation costs). Installation cost is expected to remain relatively constant and thus eventually make up to 20% of total system cost (excluding manufacturer and trade margins). The additional cost reduction of both fuel cell stack and added system are achieved by implementing fully automated processes.

Maintenance cost (OPEX) and cost of stack replacement: During the lifetime of the fuel cell prime power system maintenance has to be performed regularly – for which the customer incurs a cost. Moreover, as outlined above, the stack has to be replaced during the system life which essentially means a re-investment in the technology that the customer has to undertake.

Maintenance cost: Manufacturers, on average, currently estimate annual maintenance cost for the customer to be 60,000 EUR (excl. VAT). With increasing production volumes and experience gains for manufacturers and installers alike, maintenance costs will decrease by approximately 25%, to 45,000 p.a. EUR (excl. VAT).

Cost of stack replacement: The cost of stack replacement for the generic fuel cell system is currently 850,000 EUR per stack (incl. installation, excl. VAT). Replacement stacks will benefit earlier from volume-driven reductions of stack costs, provided that newer, cheaper stacks are compatible with older systems. Based on the industry data collected, the cost of the generic fuel cell's replacement stack is expected to fall by 40% by the time the cumulative production per company passes the threshold of 50 MW_{el} installed capacities – eventually dropping to 450,000 EUR under industrial production.

Cluster 5: Fuel cell CHP_{Natural Gas} for industrial applications (1,400 kW_{el})

Pharmaceutical and chemical production facilities are characterised by substantial power and heat demand. Fuel cell as well as other CHP technologies tackle the operator's dependency on grid prices

and increase power security. However, in the pharmaceutical and chemical sectors conventional CHP technologies such as gas turbines and gas motors have gained popularity and are commonly used solutions.

One of the reasons why stationary fuel cell technologies are particularly attractive in comparison to conventional technologies is the possibility to exploit hydrogen gained as a by-product in various chemical production processes (i.e. ammonia production process, chlor-alkali production process, etc.). Examples in this sector include companies such as NedStack and AFC Energy which have had success in implementing their fuel cell systems in Germany, the UK and the Netherlands, based on PEMFC (Proton Exchange Membrane Fuel Cell) and AFC (Alkaline Fuel Cell) technologies, respectively. Their systems apply in the chlor-alkali industry and use the hydrogen by-product to generate power and heat. However, the chlor-alkali industry is under tight scrutiny by European regulators due to mercury pollution. The European chlor-alkali industry has agreed to convert or close down most of the mercury-cell facilities by 2020.

A fully packaged fuel cell CHP system for natural gas typically features the following components:

- A stack of fuel cells that uses hydrogen to generate power and heat as a by-product
- Added system components to complete the fuel cell module, namely:
 - A fuel processing unit that reforms any hydrocarbon (natural gas, biogas etc.) to hydrogen and carbon dioxide
 - A grid-tie inverter to convert low-voltage direct current to standard alternating current
 - Balance of Plant (BOP)
- Control, interaction and feedback (e.g. smart meter)

A typical fuel cell CHP system with 1,400 kW_{el} electrical capacity is likely to have the following technical features as shown in Figure 42 – with estimated system cost that significantly decrease with increasing production volumes:

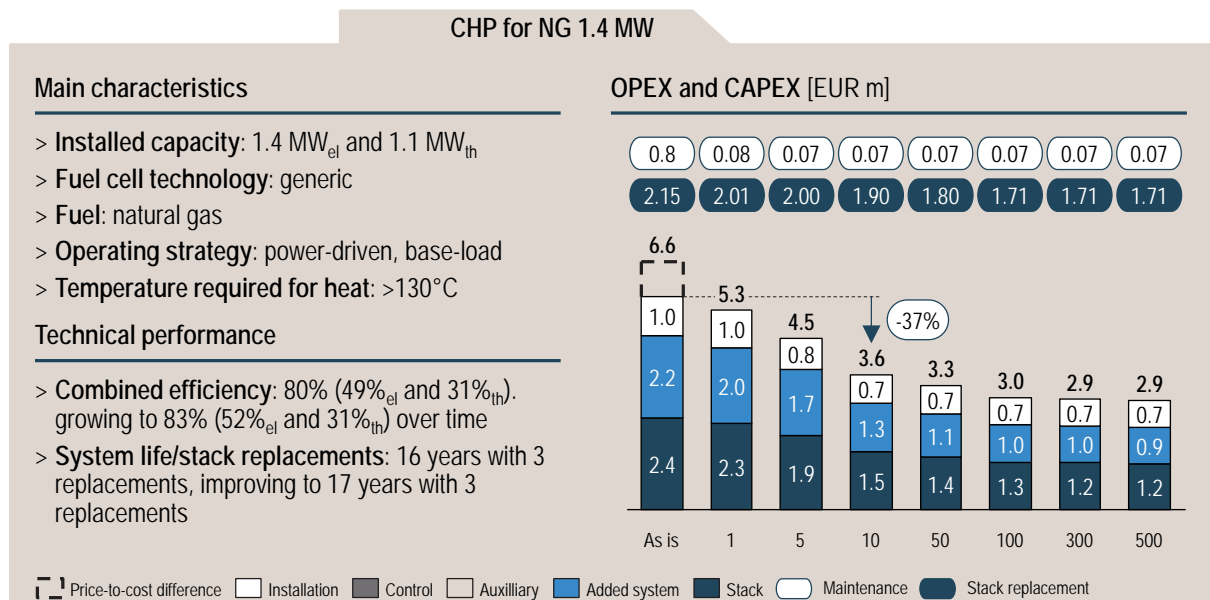


Figure 42: Technology and cost profile of generic fuel cell CHP for natural gas⁷⁰

⁷⁰ Figures produced exclude profit margins. Volumes reference cumulative production volumes per company.

Technical features:

Capacity: The generic fuel cell has an electrical capacity of 1,400 kW_{el} and thermal capacity of 1,116 kW_{th}. Amongst industry players which provided data for the computation of the generic fuel cell, the maximum thermal capacity with given electrical capacity is 1,167 kW_{th}. At lower temperatures, thermal capacities of up to 1,300 kW_{th} are possible.

Technology: The generic fuel cell is deliberately kept technology-agnostic. Dominant technologies in the industry are high-temperature fuel cells like molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC). Moreover, low-temperature fuel cells like alkaline fuel cells (AFC) are available.

Fuel: The generic system builds on existing fuel infrastructure and uses natural gas. The fuel cell can also be powered by biogas or pure hydrogen.

Operating strategy: The generic CHP natural gas fuel cell is pursuing a base-load operation strategy. System ramp-up time differs depending on fuel cell technology considered.

Efficiency: The system has an electrical efficiency of 49%_{el} and thermal efficiency of 31%_{th} resulting in a total efficiency of 80%. Due to technology improvements, the efficiency can reach 52%_{el} electrical efficiency, whereas thermal efficiency is kept at 31%_{th}. Some manufacturers expect to even reach electric efficiencies of up to 55%-60%_{el} and thermal efficiency of up to 35%_{th}. These differences are highly dependent on fuel cell technology.

System life and stack replacements: On average, industry data indicates a system design life of 16 years with three replacements of the stack during that period. The industry expects to slightly improve the system lifetime to 17 years as the technology matures with the same number of replacements. Some upsides even predict up to 21 years of system life, with two stack replacements. Industry representatives stress that the further increase of stack durability and system life remains a critical area for further technology development, and that this is not only driven by expanding production volumes but rather by more time and resources for product development as such.

Even though the system providers for the CHP natural gas system are more technologically advanced, further non-volume driven improvements are possible through innovation and R&D. The most critical are:

- Reducing fuel cell degradation, with narrower variation of cell performance to increase the lifetime of the fuel cell stack
- Increasing the total efficiency of the system to reduce operating costs
- Improving the reliability of the BoP to improve overall fuel cell performance, reduce redundancy and maintenance
- Simplifying the fuel cell system and increasing transparency (e.g. by standardising components) to enable component integration and reduce the number of components and ultimately system failures

Economic characteristics

Cost of system (CAPEX):

Current system costs differ to some extent amongst different technology types and manufacturers – however, within a standard variation of less than 10%. Currently, a 1.4 MW_{el} CHP system would cost – on average – approximately 5,640,000 EUR. The cost of system is currently dominated by the fuel cell stack, which amounts to 53% of the fuel cell module. Added system costs account for the remaining 47%. Installation cost amounts to, on average, 18.5% of the entire packaged system. When additionally considering typical OEM and trade margins (20%) as well as average anticipated installation costs, an estimated end-customer price (excl. VAT) adds up to more than 6,600,000 EUR (excl. VAT). This

hypothetical end-customer price does not consider any investment subsidies, tax credits or other policy support.

Industry players expect system costs to drop significantly, once companies' production volumes increase to standardisation and eventually fully industrialised production. The industry anticipates the following major steps and phases in the technology learning curve and the resulting cost degression:

Initial roll-out (up to 5 MW_{el} cumulative installed capacity per company): The first significant cost reduction step is expected to be achievable when companies reach the milestone of 5 MW_{el} cumulative installed capacities. On average, the industry players expect total system costs to drop by 20% (excluding manufacturer and trade margin, but including installation cost). Stack costs as well as added system costs can be reduced by competitive material sourcing and increased batch size, thus reducing set-up time, energy consumption and labour costs.

Standardisation (up to 50 MW_{el} cumulative installed capacity per company): The second important milestone is the mark of 50 MW_{el} cumulative installed capacity per company where system cost are expected to decrease by a further 30% down to 3,270,000 EUR (incl. installation costs). The anticipated cost reduction is expected to come both from the stack as well as the added system cost (i.e. up to 50% decrease) whilst installation cost is expected to decrease by 30%. Stack cost reduction can be achieved by increasing automation in the production process whilst added system costs can be reduced by improved sourcing and distributed engineering costs, as well as increased automation.

Industrialisation (beyond 50 MW_{el} installed capacity per company): Ultimately, in the range of 50 MW_{el} cumulative installed capacities per company, system costs may even decrease to 2,900,000 EUR (incl. installation cost). Stack costs can be reduced by increasing automation in stack manufacturing, improved sourcing of components and local/regional manufacturing. System simplification, whereby redundancies are eliminated, can produce important cost savings for the added system of the fuel cell. Skilled labour and the wider installation and service infrastructure could result in further cost savings.

Maintenance cost (OPEX) and cost of stack replacement:

During the lifetime of the fuel cell prime power system maintenance has to be performed regularly – for which the customer incurs a cost. Moreover, as outlined above, the stack has to be replaced during the system life which essentially means a re-investment in the technology that the customer has to undertake.

Maintenance cost: Manufacturers currently estimate, on average, the annual maintenance cost for the customer to be 83,000 EUR (excl. VAT). With increasing production volumes and experience gains for manufacturer and installers alike, the maintenance cost will decrease to 68,000 p.a. (excl. VAT), which is a better cost position compared to conventional CHP technologies with similar capacity.

Cost of stack replacement: The cost of stack replacement for the generic fuel cell system is currently 2,150,000 EUR per stack (incl. installation, excl. VAT) for the customer. Replacement stacks will benefit earlier from volume-driven reductions of stack costs, provided that newer, cheaper stacks are compatible with older systems. Based on the industry data collected, the cost of the generic fuel cell's replacement stack is expected to fall by 17% by the time the cumulative production per company passes the threshold of 50 MW_{el} installed capacities – eventually dropping to 1,700,000 EUR under industrial production.

Cluster 6: Fuel cell CHP_{Biogas} for industrial applications (400 kW_{el})

Fuel cell systems, as well as other CHP solutions, can also be fuelled by biogas. The availability of the fuel at production sites makes distributed power generation economically and environmentally very attractive.

However, the cost associated with the capture and storage of biogas can be substantial. The payback time decreases in accordance with the amount of biogas that is gained. However, large energy demand fluctuations and constant biogas production could negatively affect the net present value (NPV) calculation, due to the large required storage infrastructure.

Biogas storage is at incipient levels in most European countries. Thus, the willingness of industrial customers to invest in the storage infrastructure is highly dependent on the price of natural gas. Therefore, the future of biogas remains uncertain.

In those use cases relevant to the biogas 400 kW_{el} fuel cell system, heat plays an important role. Breweries use heat of 90 – 110°C in the brewing and glass-cleaning process. Temperature requirements in wastewater treatment facilities can also reach 130°C. High-temperature fuel cells can thus address both the power as well as the heating needs of the relevant facilities.

A fully packaged fuel cell CHP system for biogas-producing facilities typically features the following components:

- A stack of fuel cells that uses hydrogen to generate power and heat as a by-product
- Added system components to complete the fuel cell module, namely:
 - A fuel processing unit that reforms any hydrocarbon (natural gas, biogas etc.) to hydrogen and carbon dioxide
 - A grid-tie inverter to convert low-voltage direct current to standard alternating current
 - A biogas purification unit
 - Balance of Plant (BOP)
- Control, interaction and feedback (e.g. smart meter)

A typical fuel cell biogas system with 400 kW_{el} is likely to have the following technical features as shown in Figure 43 – with estimated system costs that drop moderately (compared to previously presented fuel cell systems) with increasing production volumes:

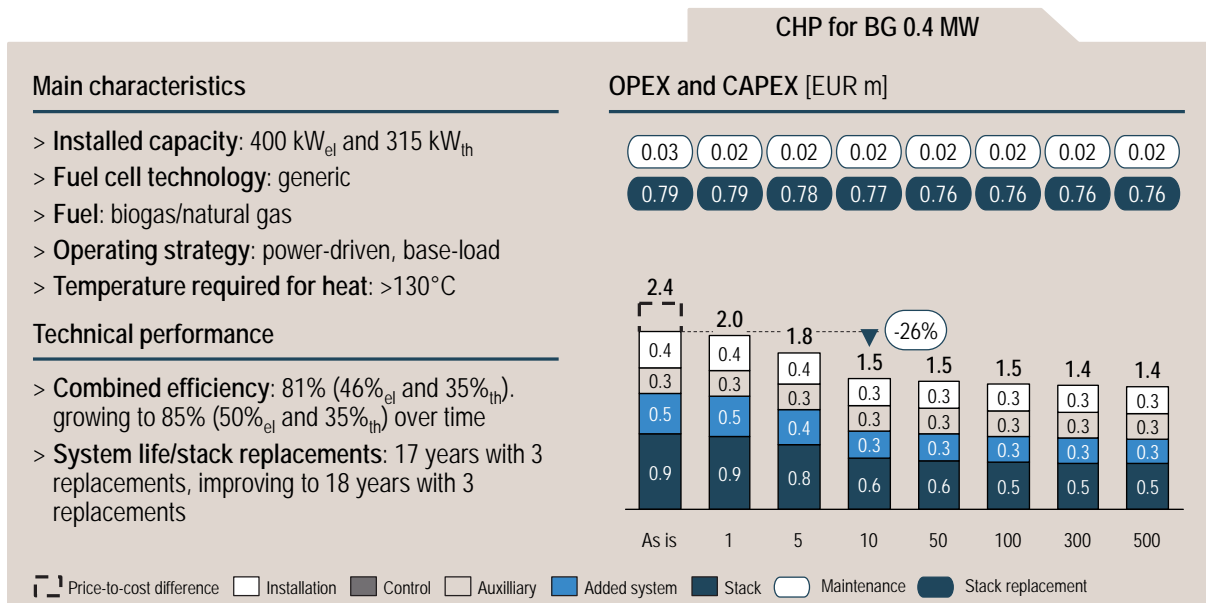


Figure 43: Technology and cost profile of generic fuel cell CHP biogas⁷¹

Technical features:

Capacity: The generic fuel cell has an electrical capacity of 400 kW_{el} and thermal capacity of 315 kW_{th}. Relative to the 400 kW electrical capacity, the thermal capacities present slight variations – from 300 to 330 kW_{th}, depending on fuel cell technology used.

Technology: The generic fuel cell is deliberately kept technology-agnostic. Dominant technologies in the industry are high-temperature fuel cells such as molten carbonate fuel cell (MCFC) and solid oxide fuel cells (SOFC).

Fuel: The generic system uses the biogas gained on site but can also use natural gas if a biogas shortage presents itself. The biogas generated from breweries or wastewater treatment facilities is purified by a biogas-purification unit.

Operating strategy: The generic CHP biogas fuel cell pursues a base-load operation strategy.

Efficiency: The generic fuel cell defined has an electrical efficiency of 46%_{el} and thermal efficiency of 35%_{th} resulting in a total efficiency of 81%. Thanks to technology improvements, the efficiency can reach 50%_{el} electrical efficiency, whereas thermal efficiency is kept at 35%_{th}. The data points provided on fuel cell efficiency are rather homogeneous with no major differences amongst fuel cell technologies and manufacturers.

System life and stack replacements: On average, current industry data indicates a system design life of 17 years with three stack replacements required during that period. The industry expects to slightly improve the system lifetime to 18 years as the technology matures with the same number of replacements. Some even predict up to 21 years of system life, with two stack replacements. Industry representatives stress that the further increase of stack durability and system life remain a critical area for further technology development that is less driven by growing production volumes but rather by the dedication of more time and resources for product development.

The non-volume driven technological improvements possible for the CHP Biogas system are highly correlated to those of the CHP Natural Gas system. Reduction of degradation rate and increase of system lifetime, increase of efficiency and BoP reliability as well as overall simplification of the fuel cell

⁷¹ Figures produced exclude profit margins. Volumes reference cumulative production volumes per company.

system are critical development levers which can be addressed through further R&D efforts. Additionally, the biogas purification unit required for biogas usage can be further developed by increasing the reliability and reducing manufacturing costs.

Economic characteristics

Cost of system (CAPEX):

Current system costs differ to some extent amongst different technology types and manufacturers – however, within a standard deviation of approximately 5%. Currently, a 400 kW_{el} CHP system would cost approximately 2,075,000 EUR. The system cost is currently dominated by the fuel cell stack, which amounts to 65% of the fuel cell module. Added system cost accounts for the remaining 35%. An auxiliary biogas purification unit is required, adding approximately 300,000 EUR. Installation accounts for an average of 20% of the entire packaged system. When additionally considering typical OEM and trade margins of 20% as well as average anticipated installation costs, an estimated end-customer price (excl. VAT) amounts to more than 2,400,000 EUR (excl. VAT) for the 400 kW_{el} generic CHP system that we consider as a representative product for the biogas segment. This hypothetical end-customer price does not consider any investment subsidies, tax credits or other policy support.

Industry players expect system cost to drop moderately, once companies' production volumes increase to standardisation and eventually fully industrialised production. The level of experience is higher than in other technology clusters. The following major steps and phases in the technology learning curve and resulting cost degeneration are expected:

Initial roll-out (up to 5 MW_{el} cumulative installed capacity per company): The first significant cost reduction step is expected to be achievable when companies reach the milestone of 5 MW_{el} cumulative installed capacities. On average, the industry players expect total system cost to drop by 12% (excluding manufacturer and trade margin, but including installation cost). Stack cost reduction can be achieved by increased automation in the production process. Added system costs can be reduced by improved sourcing, distributed engineering costs, improved infrastructure as well as increased automation.

- **Standardisation** (up to 50 MW_{el} cumulative installed capacity per company): The second important milestone is the mark of 50 MW_{el} cumulative installed capacity per company where system cost are expected to decrease by a further 18% down to then 1,500,000 EUR (incl. installation costs). The anticipated cost degeneration is expected to come both from the stack as well as the added system costs (i.e. up to 35% decrease, respectively) whilst installation costs are expected to decrease by 25%. Stack cost reduction can be achieved by increased automation in the production process whilst added system costs can be reduced by improved sourcing and distributed engineering costs, as well as increased automation.
 - **Industrialisation** (beyond 50 MW_{el} installed capacity per company): Ultimately, in the range of 50 MW_{el} cumulative installed capacities per company, system costs may even decrease to 1,400,000 EUR (incl. installation costs). Stack costs can be reduced by increased automation in stack manufacturing, improved sourcing of components and local/regional manufacturing. System simplification, whereby redundancies are eliminated, can produce important cost savings for the added system of the fuel cell. Skilled labour and the wider installation and service infrastructure could result in further cost savings.
- **Maintenance cost (OPEX) and cost of stack replacement:** During the lifetime of the fuel cell prime power system maintenance has to be performed regularly – for which the customer incurs a cost. Moreover, as outlined above, the stack has to be replaced during the system life which essentially means a re-investment in the technology that the customer has to undertake.

- **Maintenance cost:** Manufacturers currently estimate, on average, an annual maintenance cost for the customer of 25,000 EUR (excl. VAT). With increasing production volumes and experience gains, this is projected to decrease by ca. 20% to 20,000 EUR p.a. – a better cost position compared to conventional CHP technologies with similar capacity.
- **Cost of stack replacement:** The cost of stack replacement for the generic fuel cell system is currently 790,000 EUR per stack (incl. installation, excl. VAT) for the customer. With regard to the biogas segment, the most important cost-down effects are expected to be reached in the mid-term, both with regard to the fuel cell stack as well as costs of installation. This translates into a leaner cost reduction for the stack replacements. Total costs are thus expected to decrease to 750,000 EUR by the time the industrialisation phase is reached.

Key learnings from Chapter D

- Six generic fuel cell systems across three market segments are within the scope of this study
- The systems were derived on the basis of technical and economic data delivered by industry members
- Volume increases are projected to deliver CAPEX reductions
- Increasing automation may lead to substantial cost reductions
- The industrial segment has very specific technical requirements

E. Demand-side requirements and technology benchmarking

This chapter analyses the technical, economic and environmental performance of distributed generation from stationary fuel cells in different use cases across the pre-defined market segments. A thorough benchmarking analysis will highlight the substantial benefits that the technology holds both for individual users as well as greater communities and the energy system at large. We will also address the shortcomings. We begin by analysing fuel cell mCHPs in 1/2-family dwellings, then look at apartment and commercial buildings, before benchmarking larger stationary fuel cells in specific industrial applications. The following analysis exclusively covers the primary market for the fuel cell, i.e. those buildings already utilising a gas solution to meet their heating requirements.

Methodology: The benchmarking analysis

This section briefly outlines our methodology of benchmarking stationary fuel cells with competing conventional technology as far as it concerns all benchmarking. The objective of the benchmarking exercise is to show and substantiate the practical readiness of stationary fuel cells in specific use cases, outline their competitive performance vis-à-vis conventional technologies in economic, environmental and other terms, and project important developments in the future. Thereby, the benchmarking shall serve as the analytical basis to single out specific opportunities and cases for successful commercialisation of stationary fuel cells.⁷²

Scenarios: As a starting point, we stage the benchmarking in the **three different energy scenarios** that paint a distinct picture of long-term trends in Europe's energy landscape characterised by different developments of energy prices (particularly natural gas and electricity) as well as prices on CO₂ emissions in the four focus markets of this study.

Use cases: Against the backdrop of the three scenarios, we define, for each market segment, **specific use cases** for stationary fuel cells, e.g. different types of residential or commercial buildings as well as industrial applications. These use cases are characterised by different requirements, for example their annual heat and power demand, peak loads and load profiles given the size, insulation and consumption patterns of the building and its users. Along these requirements, we define these use cases as realistic and representative "case studies" that accurately depict the demand-side view and thus real-life decision-maker perspectives. Moreover, the more than 50 use cases in the scope of the analysis allow for relative comparisons of different settings in which fuel cells operate to determine the best opportunities for commercialisation in terms of use-case fit.

Decision perspective: The benchmarking analysis assumes that the decision maker in the respective use case **has to make a decision in any case** regarding a distributed generation system, e.g. because the heating solution of the building in question has to be replaced. However, we limit the decision to the actual heat or power generation technologies and assume that further essential infrastructure is in place. This concerns particularly any hot water (and if applicable hot drinking water) tanks, connections to the gas as well as electricity grid, other fuel-supply infrastructure, chimneys and all necessary piping. Moreover, we assume that the decision maker considers a uniform time horizon for comparing different DG technologies (e.g. heating solutions); in our case we assume 15 years.

Technology pool: In view of the imminent decision for a power or heat generation technology for the specific use cases, we define a **pool of competing technologies** that is able to meet the use case's

⁷² In general, the methodology leans on other state-of-the-art, use-case based and decision-oriented analyses, in this context particularly IFEU (2012)

requirements, e.g. for a residential building the combination of a state-of-the-art gas-fuelled condensing boiler with independent grid power supply. The benchmarking pool considers all relevant technologies available today with a clear outlook on their further progress over the next decades. For conventional technologies (e.g. boilers, solar thermal or PV, heat pumps, engine- or turbine-based CHP) we consider current products in the market – with their current technical, economic and ecological features as well as any further development and cost reduction potential. To obtain all relevant technical and economic KPIs, we researched real-life products in the market that were peer reviewed by coalition members with broad product portfolios of conventional heating solutions. For the stationary fuel cell solutions, we rely on the generic fuel cells that we determine through the clean team process from industry data (see previous sub-chapter).

Technical performance in use case: With the use case requirements and the technology pool at hand, we then examine the specific technical performance of each technology in each use case. The **ultimate performance context for the benchmarking is the supply of the use case in question with heat or power** for the period of one year – depending on whether heating or power supply is predominantly driving the distributed generation. Using specific heat-load profiles of each use case and the technology characteristics, we model the heat generation of different heating technologies such as condensing boilers, heat pumps and solar thermal collectors. For determining the technical performance of CHP technologies (internal combustion engine, Stirling engine or fuel cell), we simulate their technical performance using industry-standard simulation tools and software (e.g. VDI guideline 4656 and its applicable software with standard load profiles for heat and power consumption in residential buildings) where use cases are structurally similar (e.g. residential buildings). Results are cross-checked with alternative software and modelling tools from Coalition members as well as real-life data available from past or ongoing demonstration projects, e.g. Callux in Germany. For use cases with more specific requirements (e.g. hospitals), we employ customised models relying on fundamentals (e.g. weather data, use-case-specific process demands). For CHP technologies, the simulation generates essential technical performance indicators for each use case such as the heat coverage of the CHP module and any auxiliary boiler, the power production of the CHP module, the CHP power consumed on site as well as the power feed-in. Wherever possible, we challenge our simulation results with industry experience from real-life cases, for example data gathered during the Callux field test of fuel cell mCHPs in 1/2-family dwellings across Germany.

Based on the technical performance of different technologies for distributed generation in specific use cases, we are able to benchmark their performance in economic, environmental and other terms.

Economic benchmarking: The main use-case-specific benchmarking context is the supply of the use case with heat or power for the period of one year. Consequently, our main economic benchmarking criterion is the **Total Annual Heating Costs (or Total Cost of Ownership p.a.)** for each technology in the pool for each use case. For the example of residential use cases, the benchmarking thus answers the following question: How much does it cost to heat a family home for one year with different technology solutions? The total annual heating costs comprise capital cost, maintenance cost, and net energy cost.

Capital cost: We calculate annual capital cost as an annuity of the initial capital expenditure (CAPEX) for the technology over the benchmarking horizon (here 15 years) as well as an annuity of the present value of any essential re-investment over the course of the horizon. We assume an interest rate of 6% p.a. for all calculations. This way, all technologies are benchmarked with a total useful life equalling the benchmarking horizon, i.e. there are no residual values after 15 years.

Maintenance cost: We consider technology-specific annual maintenance cost for different market segments and sub-segments that are assumed to be constant over the benchmark horizon.

Net energy cost: Most importantly, we consider the variable cost of energy in order to supply the building with heat or power (depending on the use case). For all technologies, this concerns the fuel for heat and/or power generation. Fuel costs are determined by fuel type (natural gas, biogas for boilers and CHP technologies, electricity for heat pumps), the amount of fuel consumption (as determined by the efficiency of the technology) and fuel prices (as assumed through different scenarios). Moreover, cogeneration has to be properly considered for all CHP technologies. In heat-driven use cases, i.e. wherever heating a building is predominantly driving the technology decision, power is an "add-on" product of heating from CHP technologies (e.g. the fuel cell). The benefits from this power generation reduce the overall annual energy cost for heat and power for the use case. We thus reduce the total annual heating cost accordingly. Specifically, we consider a credit for avoided power purchase from the local utility for all electricity that is produced and consumed on site. Moreover, we include the direct proceeds from all electricity that is produced on site, but fed into the power grid. For own consumption, we calculate with the respective retail power price, for power feed-in we consider power prices at the exchange and a credit for avoided grid fees. We vary all electricity prices across our three energy scenarios.

Clean-policy analysis: In our initial economic benchmarking, we do not consider any policy support schemes for the generic stationary fuel cell systems defined above or for any competing technology (with the sole exception of feed-in tariffs for solar PV where we include the existing, well established and long-term national regimes). Thus, we benchmark different heating technologies according to their stand-alone performance.

Environmental benchmarking: The environmental dimension of comparing the performance of different technologies for distributed generation in different use cases concerns various types of emissions. As the main benchmarking context is the supply of the use case with heat or power for the period of one year, the comparison of different technologies thus answers the question: Which technology supplies the use case with heat or power with the least emissions for one year? Consequently, we consider different emission types, namely greenhouse gas emissions, pollutants, particulates and noise. For greenhouse gases, we assess direct emissions of carbon dioxide (CO₂) and for pollutants direct emissions of nitrogen oxide (NO_x). When benchmarking the CO₂ and NO_x emissions of different technologies, we chose – after careful review of literature on emissions benchmarking – the "total-balance methodology" for comparing use-case specific annual emissions. Accordingly, every use case has to account for all emissions originating from its annual energy consumption (heat and electricity) on site. For a conventional solution of a gas condensing boiler with grid power supply, this means for example that total emissions comprise firstly all emissions from natural gas consumption (as determined by the thermal efficiency of the boiler as well as the direct emissions factor of natural gas as fuel) and secondly all emissions from power consumption (as determined by the average emissions footprint of the electricity mix in the respective country). For a CHP solution, the emissions from natural gas consumption account both for heat and power. Consequently, the power-related emissions of the use case are reduced to the residual amount of electricity that is actually taken from the grid. For power feed-in we attribute an emissions credit to the use case that is determined by the footprint of the electricity mix in the respective country, as this electricity is consumed elsewhere.

Benchmarking residential segment: Competitive positioning of the fuel cell system

As demonstrated above, the residential segment has great potential for the application of standardised stationary fuel cells as integrated mCHPs.⁷³ Whilst the industry aims to supply uniform products for all kinds of 1/2-family dwellings, it is nevertheless important to distinguish individual opportunities and challenges for CHP technology in different types of buildings across different markets. We thus consider a portfolio of different use cases for our benchmarking analysis. This section reviews use cases displaying the characteristics and particularities of buildings in the specific countries. Please note that buildings pertaining to the multi-family building category may also be served by similar technologies as those covered in this section, if the heating requirements are within an appropriate range.

Definition of use cases: The importance of analysing stationary fuel cells in specific use cases

This section gives an overview of the main features of the use cases that are used for the technology benchmarking analysis. We define different types of representative but distinguishable buildings across different markets. Figure 44 gives an overview of the selection.

ID	Location	Construction year	Renovation work	Share in building stock	Heated space [m ²]	Annual heat demand incl. DHW [kWh]	Power-to-heat demand ratio
DE1	Gütersloh (DE)	2009	-	4%	130	10,836	48%
DE2	Hamburg (DE)	1978	Yes	10%	110	18,092	29%
DE3	Munich (DE)	1964	Yes	27%	103	21,438	24%
DE4	Osterfeld (DE)	1948	No	8%	150	38,332	14%
UK1	Brighton (UK)	2008	-	1%	110	11,826	47%
UK2	London (UK)	1970	Yes	19%	79	10,348	54%
UK3	London (UK)	1970	No	49%	79	13,719	41%
UK4	Glasgow (UK)	1945	No	5%	69	20,384	27%
IT1	Rome (IT)	2008	-	2%	174	13,947	32%
IT2	Milan (IT)	1975	Yes	33%	199	18,342	24%
IT3	Milan (IT)	1975	No	30%	199	29,393	15%
IT4	Rome (IT)	1919	No	17%	115	35,448	13%
PL1	Szczecin (PL)	2003	-	9%	187	19,570	14%
PL2	Krakow (PL)	1993	Yes	8%	153	24,771	11%
PL3	Warsaw (PL)	1986	No	58%	136	31,247	9%

⁷³ For benchmarking stationary fuel cells in residential buildings – here specifically 1/2-family dwellings – we focus on the majority product type in the European portfolio, i.e. integrated, heat-driven fuel cell mCHPs targeting the heating market. Main competitors are thus conventional heating solutions; homeowners face the inevitable decision of a technology solution to heat their home.

PL4	Poznan (PL)	1950	No	25%	98	37,579	7%
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Figure 44: Residential buildings defined as use cases⁷⁴

European residential buildings are very diverse in several dimensions. Not only do dwellings differ in terms of heating requirements, given climatic and geographic differences, they also differ in the degree of renovation and the consumption habits of the residents. An additional dimension to the representativeness in the building stock is the size of the living space. In the UK the largest share of dwellings (33%) is between 70-80 m².

The heat demand of a household is determined primarily by outside weather conditions. Italy receives ca. 500 kWh of sunlight more per square metre than the UK and, consequently, Italian residents don't heat their home as often and as extensively as their British counterparts. Demand is also determined significantly by the degree of building renovation through window double glazing, cavity-wall and roof insulation. In Germany 65% of the buildings constructed before 1980 are renovated. In Italy on the other hand, this share amounts to ca. 40%. Along these lines, the fifth column of Figure 44 includes a percentage figure for the representativeness of the use case in the building stock. This indicator relies both on the age distribution of 1/2-family dwellings in the national building stock and the extent to which buildings of this age are renovated. The figures above consider that Italy has the oldest building stock, and only a comparatively small fraction of Polish buildings have high energy efficiency standards. All these factors taken together generate use case specific heating profiles. An exemplary aggregated heat-load profile over the period of one year is displayed in Figure 45.

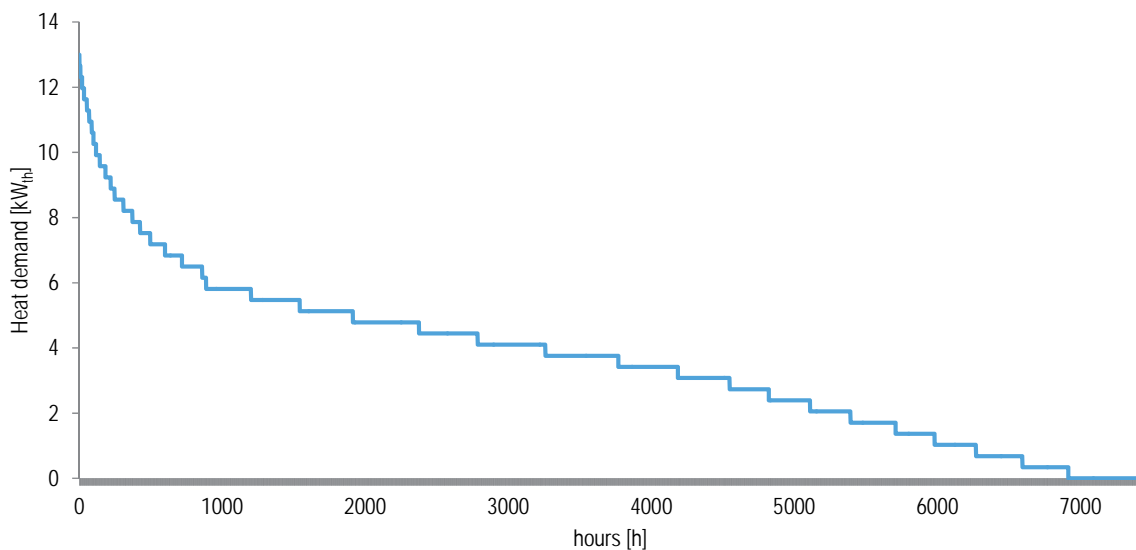


Figure 45: Exemplary heat-load profile of a German, partially renovated 1/2-family dwelling⁷⁵

Electricity requirements differ considerably in Europe and amongst households. The UK has the greatest power consumption per household in our focus group, whereas Poland has the lowest.





⁷⁴ Cf. Tabula (2012), Verbraucherzentrale NRW (2014), Energy Savings Trust (2014), Roland Berger modelling

⁷⁵ The profile corresponds to the use case DE3 in Figure 44, Roland Berger modelling

Therefore, the power-to-heat ratio in Polish buildings is significantly lower than in the UK, in spite of the heating requirements per square metre [m²] being comparable. All cases above are based on a four-person household in order to ensure consistency.

The availability of heating infrastructure in a specific region influences the technology solution a customer chooses. For the sake of comparability, this study assumes that all dwellings already have access to the gas grid and could thus potentially use a gas-fuelled fuel cell technology. However, buildings vary in terms of their technological heating infrastructure and the regional availability of appliances. The solutions may vary accordingly. Whereas wall-hung boilers are commonplace in the UK, the same is not true for continental Europe. Poland has an elaborate district heating infrastructure and German households rely predominantly on floor-mounted solutions. This point may prove crucial with regard to the physical compactness requirements of the CHP system. Furthermore, the technological specification of the fuel cell in practice depends on the flow temperature of the heating circuit, which in turn depends on whether under-floor heating or radiators are installed and the outside temperature.

This section identifies criteria relevant to a potential customer's purchase, and highlights the drivers of the decision. The decision maker will approach the topic with a strong focus on the economics and environmental performance.

Description	Decision criteria	Relevance
Economic Performance	<ul style="list-style-type: none"> > Initial investment cost > Total cost of ownership 	
Environmental Performance	<ul style="list-style-type: none"> > Emission performance > Application noise 	
Reliability	<ul style="list-style-type: none"> > Independence from the grid > Uninterrupted power supply > Independence from electricity price movements 	
Other	<ul style="list-style-type: none"> > Physical compactness > Novelty and innovation 	



 Decisive
  Irrelevant

Figure 46: Demand-side requirements of decision makers in the residential market segment

The initial investment – i.e. the up-front "price tag" of the technology – plays a decisive role in the decision making process. With regard to environmental concerns, the consumer is interested in the extent to which his investment entails a reduction in greenhouse gas emissions, as well as savings in pollutants and particulates. Furthermore, the noise of the application influences his decision. Other considerations, such as physical compactness and the modernity of the technology are considered to be less uniform, given elaborate heterogeneity in consumer preferences. Several 1/2-family dwellings are expected to switch their heating solution. The array of criteria defined above is naturally not static, but subject to the individual circumstances of the decision maker. There is a clearly distinguishable path dependency in the decision for a heating system. Households in Germany, for example, relying on heating oil, may decide to remain with this technology. It is expected that 82% of the German decision makers in this situation will do precisely that, and that only 10% will switch to a gas-based solution. The

overwhelming majority of the households already relying on gas-based solutions are expected to renew their gas boiler (92%). Only 5% are expected to choose heat pumps over gas. Those residential buildings currently relying on power for heat production are deemed remarkably flexible with regard to their propensity to switch. 34% are expected to switch to heat pumps and 10% to district heating. Only ca. half will renew their existing technology.⁷⁶

Definition of technology pool: Competing appliances in the primary market

Eight technologies comprise the technology pool for the residential segment. They are summarised in Figure 47. We included a condensing gas boiler, a gas boiler including solar thermal collectors to cover conventional heating technologies based on gas. Furthermore, we included an internal combustion engine and a Stirling motor in the analysis given that these technologies compete directly with the stationary fuel cell in the CHP segment. Heat pumps, both air-to-water and ground-to-water, were also included in the analysis. Moreover, one specification included an air-to-water heat pump in combination with PV. The selection guarantees unambiguous benchmarking against not only conventional heating solutions such as the gas condensing boiler, but also modern alternatives such as heat pumps and competing CHP technologies. Moreover, district heating is included in the technology benchmark. The latter presupposes the corresponding heating infrastructure to be in place. Figure 47 includes specifications for both the main and any auxiliary heating system (if applicable). This may be an additional boiler to cover peak heat demand or solar thermal collectors for hot water production. An auxiliary system may also produce power, such as solar PV. The data on system prices disclosed in the following table excludes VAT.

⁷⁶ Cf. Shell-BDH

Unit	Gas boiler (condensing)	Gas boiler (cond.) with solar thermal	Air-to-water heat pump	A-HP	Air-to-water heat pump with PV	A-HP PV	Air-to-water heat pump with PV	A-HP PV	Ground-to-water heat pump	G-HP	Ground-to-water heat pump	G-HP	ICE CHP combustion engine	MCHP Stirling engine	MCHP with Stirling engine	District heating	DH	Fuel cell CHP	FC CHP ⁷⁷
Abbreviation	ID	Gas	Gas ST	A-HP	A-HP	A-HP	A-HP	A-HP PV	A-HP PV	G-HP	G-HP	G-HP	ICE CHP	MCHP	MCHP	DH	DH	FC CHP ⁷⁷	
Thermal capacity of main system	[kW _{th}]	<35	<35	13	35	35	13	35	35	13	35	35	2.5	5.3	5.3	-	-	1.45	
Electrical capacity of main system	[kW _e]	-	-	-	-	-	-	-	-	-	-	-	1	1	1	-	-	1	
Thermal capacity of auxiliary system	[kW _{th}]	-	3,3	-	-	-	-	-	-	-	-	-	<35	<35	<35	-	-	<35	
Elec. capacity of auxiliary system	[kW _e]	-	-	-	-	-	1.5	1.5	1.5	-	-	-	-	-	-	-	-	-	
Thermal efficiency of main system	[%]	95	95	370	350	350	370	370	350	400	480	65	81	81	81	-	-	52	
Electrical efficiency of main system	[%]	-	-	-	-	-	-	-	-	-	-	26.3	15	15	15	-	-	36	
Thermal efficiency of auxiliary system	[%]	-	40	-	-	-	-	-	-	-	-	95	95	95	95	-	-	95	
Elec. efficiency of auxiliary system	[%]	-	-	-	-	-	16	16	16	-	-	-	-	-	-	-	-	-	
Total cost of packaged system	[EUR]	1,740-2,800	4,485-7,172	7,268-13,089	16,442-17,226	16,442-17,226	9,960-16,015	9,960-16,015	18,829-20,445	13,972-18,500	26,345-33,640	16,605-20,205	15,205-20,478	15,205-20,478	15,205-20,478	2,600	2,600	31,150	
(A) Cost of system	[EUR]	1,500-2,000	3,500-4,700	6,468-12,290	16,170-17,170	16,170-17,170	9,702-14,415	9,702-14,415	18,295-18,480	13,142-15,490	25,345-30,039	15,205-15,480	13,805-15,480	13,805-15,480	13,805-15,480	2,300	2,300	-	
(B) Cost of installation	[EUR]	240-1,060	985-2,960	272-1,056	272-1,056	272-1,056	533-1,965	533-1,965	533-1,965	830-3,000	1,000-3,600	1,400-5,000	1,400-5,000	1,400-5,000	1,400-5,000	300	300	-	
Annual maintenance cost	[EUR]	50-200	70-260	40-130	40-130	40-130	90-310	90-310	90-310	40-130	40-130	900-1,100	120-430	120-430	120-430	80	80	500	
Major re-invest (if applicable)	[EUR]	-	-	-	-	-	-	-	-	-	-	-	-	1,500	1,500	-	-	6,700	
Lifetime	[years]	15	15	15	15	15	15	15	15	15	15	15	15	15	15	-	-	15	

Figure 47: Competing heating technologies in 1/2-family dwellings

⁷⁷ Industry experts expect the technological characteristics, particularly the efficiencies, to improve over time. For more information, please see Chapter E

⁷⁸ All cost figures are disclosed in EUR excluding VAT

Economic benchmarking: An assessment of annual heating costs

The economic performance of the fuel cell plays an important role for potential customers, as discussed in the previous section. Hence, the following section will provide a detailed assessment of the annual heating cost a specific use case would encounter, if a specific technology was chosen.

Excursus and recap: Underlying energy prices

Figure 48 displays the **energy prices** underlying the calculation of the fuel costs for 2014 and 2017 in the Patchy Progress scenario. Figure 17 gives an overview of the overall price developments in all three scenarios. For the sake of analytical clarity, assumptions are made on the energy price landscape such as a constant share of grid fees in the retail power price of 20%, and a constant share of taxes and levies across all four focus countries. Furthermore, the policy environment is analytically streamlined by assuming a persistence of the current feed-in tariffs from PV.

Production premiums, feed-in tariffs and capacity support for CHP are disregarded in the analytical benchmarking in order to provide an unbiased account of the economic performance of the fuel cell.

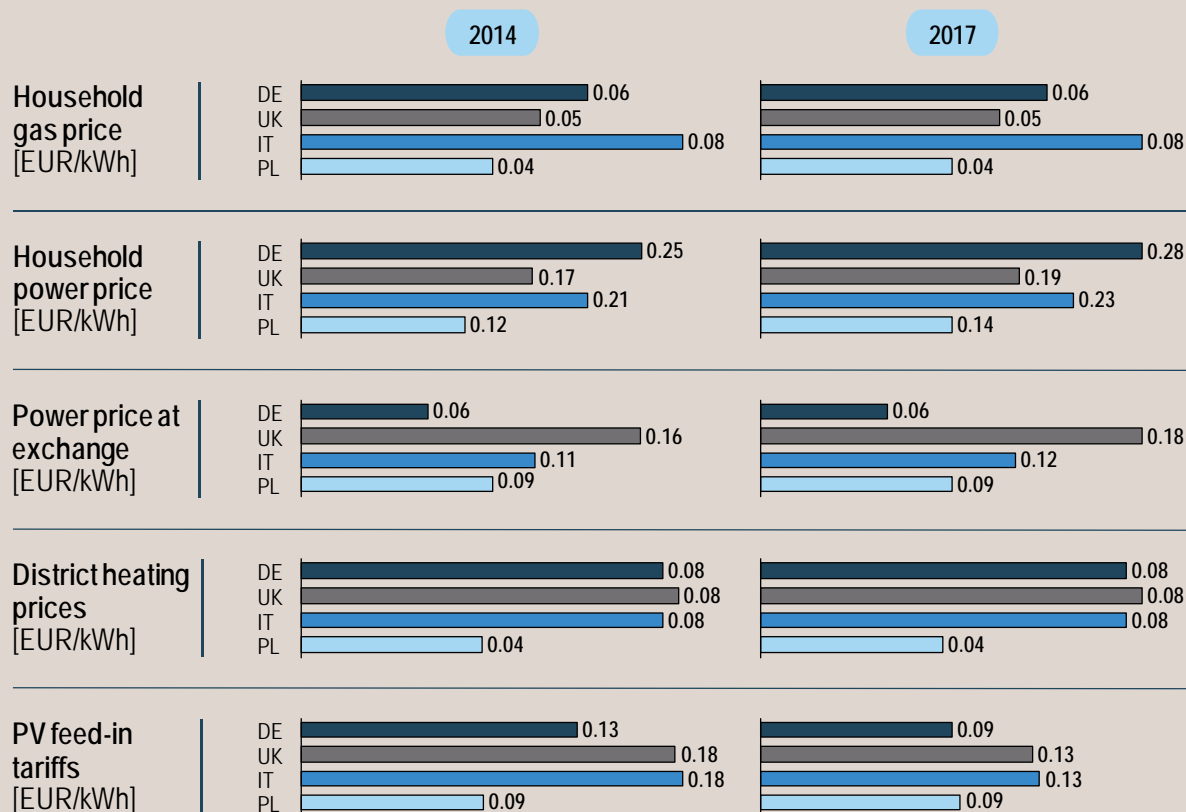


Figure 48: Exemplary selection of energy prices assumed for the benchmarking⁷⁹

The following example (Figure 49) explores the details of the benchmarking calculation as performed on a partially renovated building in Munich from 1964, with a total annual heat demand of 21,438 kWh (use

⁷⁹ Sources: Eurostat (2014), RES Legal (2014), European Commission, E.On UK, Roland Berger (May 2014)

case DE3 in Figure 44). The calculation performed is comparable for all other use cases covered by this study.

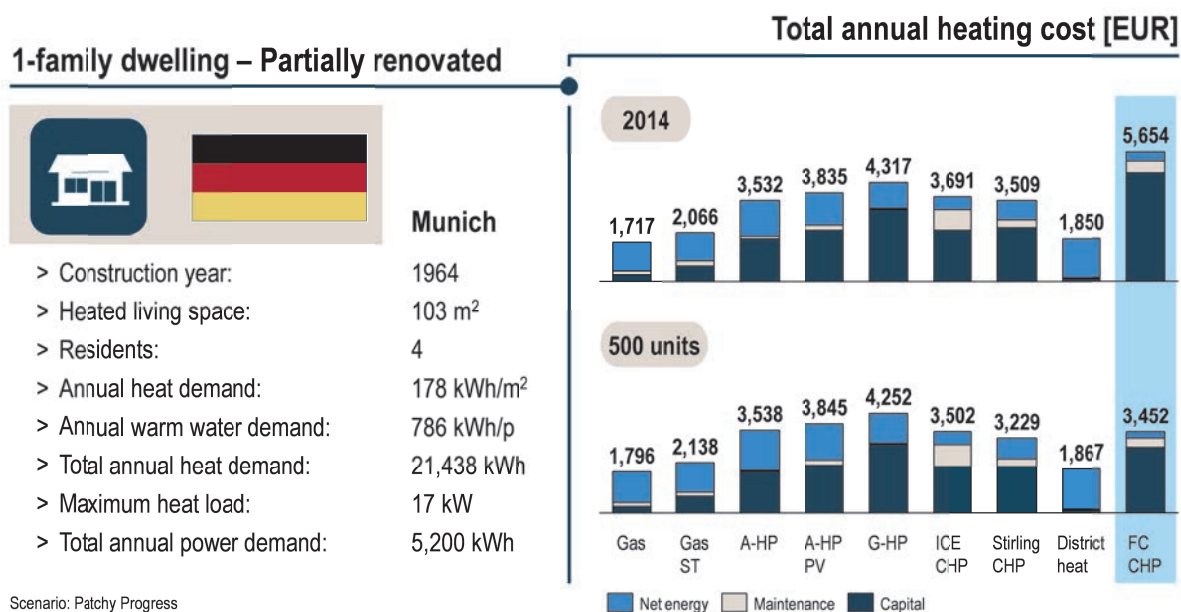


Figure 49: Economic benchmarking in a German partially renovated, 1/2-family dwelling⁸⁰

The heat requirements of a common gas boiler are determined by the use case specific maximum heat load. We distinguished two boilers for the analysis with capacities of 13 and 35 kW, respectively, which can be modulated to fit a use case specific heat-load profile. The corresponding annuity was calculated using investment and maintenance cost data specific to the composition of the heating system. Given a thermal efficiency of 95%, the fuel input is calculated and multiplied with country level energy prices, determined in the scenarios. If the heating system includes solar thermal collectors for hot water production the calculation is adjusted and assumed to cover 50-80% of demand, depending on the geography of the building. The additional investment is added to the annuity, and the fuel savings through the auto-production of heat are deducted. The 35 kW condensing boiler installed in the DE3 use case costs 2,800 EUR (excl. VAT) including installation. Given an assumed lifetime of 15 years and 6%, the annualised value is calculated to be 288 EUR in 2014. As the use case requires the boiler to cover 100% of the 21,428 kWh heat demand, 22,566 kWh of gas are necessary given the efficiency of the system. Granted the German household gas prices displayed in Figure 48, the total fuel cost amounts to 1,279 EUR. Adding an annual maintenance cost of 150 EUR, the annual heating cost totals 1,717 EUR as displayed in Figure 49. If the boiler solution is complemented by solar thermal collectors, the latter covers ca. 60% of the DE3 hot water demand. The auxiliary technology costs 2,700 EUR and an additional 1,300 EUR for installation in Germany. However, the fuel cost is reduced as only 91% of the household heat demand must be met by the condensing boiler. The corresponding annualised figure is 2,066 EUR.

⁸⁰ For our analysis, cumulative production volumes of 500 units per manufacturer are expected by 2017. Energy price developments and cost-down developments for other technologies are considered accordingly under the Patchy Progress scenario. The benchmarking considers the use case DE3 in Figure 44.

Analogous to the calculation for the gas condensing boiler, the total annual heating cost is calculated for the **heat pump**. The air-to-heat technology uses electricity to power a fan, which leads the outside air over a collector. The heat in the air temperature is transferred to a refrigerant, which is used to heat the rest of the system. The ground source heat pump uses a comparable system but extracts heat from the ground using pipes buried in the garden. Electrical power being the input, Figure 47 presents the corresponding efficiencies (COP) that determine the power consumption of the heat pump. The initial investment cost excluding VAT was given for 2014. If a PV module is installed in combination with the heat pump, the module costs were added to the overall price of system, whereas the fuel costs are credited with the revenue from feed-in and the avoided power purchase. Regional differences in sunlight hours and intensity are key in determining the economic performance of the combination. The 35 kW heat pump system for the DE3 case has a system cost of 18,300 EUR including 800 EUR installation cost. Given an assumed lifetime of 15 years and 6% interest, the annualised value is calculated to be 1,884 EUR in 2014. As Figure 47 shows, the efficiency of the main system is 350% implying 6,125 kWh electricity demand which translates into 1,548 EUR fuel costs, given German electricity prices. With an additional 100 EUR of maintenance cost, the total annual cost of heating is calculated to be 3,532 EUR in 2014, ca. twice the price of the boiler solution. The mathematical derivation for the ground-to-water heat pump is performed identically. The calculation of a combined PV and heat pump solution assumes 8 m² of PV installation (approximately 1 kW_{el} for 2,300 EUR. Given 1,311 kWh/m² the DE3 use case produces 989 kWh of electricity throughout the year. The use case's heat profile assumes an approximately 30% share of self-consumption whereby 75 EUR of grid purchases were avoided, whilst the remaining production is fed into the grid and remunerated with 90 EUR. The results are summarised in Figure 49 above.

CHP technologies have the advantage of producing power whilst producing heat. Moreover, the CHP capacities are given, as displayed in Figure 47. Considering this information, the share of heat which is covered by the system is calculated using state-of-the-art modelling software. The remaining heat demand was assumed to be covered by an auxiliary boiler system for peaks. The heat demand covered by the main system is often above 90% for new builds, whereas the share varied strongly for older und non-renovated buildings. In the light of its high thermal capacity, the Stirling motor is often able to produce a substantial share of the heat demand. The fuel cell on the other hand, is able to produce a comparably higher amount of electricity, given its high electrical efficiency. Thereby, the deduction from the fuel costs through revenues from feed-in, and avoided power purchases are substantial. In the DE3 case, the investment costs for the internal combustion engine and the Stirling motor are 21,500 and 22,500 EUR, respectively. These figures already include the costs for auxiliary boilers to cover peak loads. The CAPEX annuities are calculated to be 2,214 and 2,317 EUR. In terms of maintenance cost, the combustion engine (900 EUR) features significantly higher cost than the Stirling engine (350 EUR). The 2.5 kW thermal capacity of the combustion engine covers 63% of the DE3 heat demand, whereas the Stirling motor covers 99%. During the runtime hours, the combustion engine produces 5,735 kWh of electricity, 55% of which are consumed by the household. The Stirling motor produces 3,586 kWh, 47% of which are fed in. Given capacity and efficiency a fuel cost of 1,651 EUR is calculated for the combustion engine, of which 1,074 EUR are deducted due to power generation. The Stirling motor would account for expenses totalling 1,501 EUR, of which 659 EUR are deducted. In terms of total annual heating cost, the combustion engine lies above the Stirling engine in 2014 with 3,690 and 3,509 EUR, respectively.

The district heating connection is assumed to cost 2,600 EUR in total as initial capital expenditure for the household. In total, the capital expenditure for the homeowner thus includes the cost of the

distribution grid, the consumer interface and the installation of the consumer interface.⁸¹ For the assessment of the variable energy cost, we consider the building's annual heat demand (here 21,428 kWh) and multiply by an average, assumed price for district heating (here a German average price of 0.08 EUR/kWh for the 2014 benchmarking as seen in Figure 48). Similarly, we assume average district heating prices for the UK, Italy and Poland. In the case of the German partially renovated building displayed above, district heating yields the lowest net energy costs and the second lowest total annual heating costs that include annualised capital cost and maintenance cost.⁸²

The generic fuel cell system outlined in Chapter D is assumed to cost 39,295 EUR as of now, excluding VAT. This amount includes two stack changes over the system lifecycle of 15 years. Figure 50 shows the annualised value calculated from this sum with a 6% interest rate on the very left. The annual maintenance cost of 500 EUR and the net energy cost are added to the annuity. In accordance with our energy modelling approach, a 48% heat coverage share is determined. The data displayed in Figure 50 correspond to the cost developments outlined in the "Patchy Progress" scenario. This calculation is directly comparable to the conventional technology costs, including a boiler annuity of 1,717 EUR and grid electricity for 1,314 EUR annually. We observe a 3,937 EUR difference.

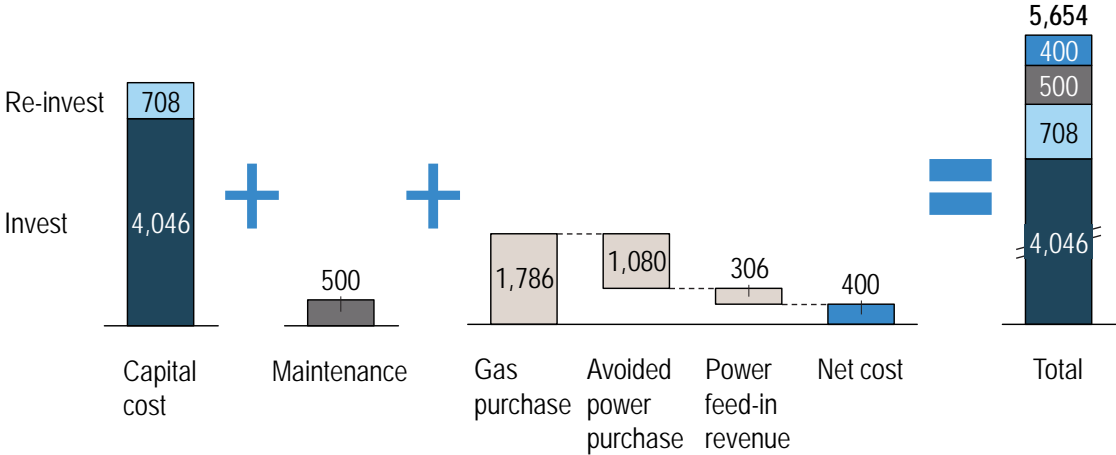


Figure 50: Exemplary calculation of the total annual heating cost for a household [EUR]⁸³

Equivalent benchmarking analyses are performed for the remaining 15 use cases. Figure 51 displays the ratio of fuel cell to total annual heating cost over competing technologies in 2014. Those cases where the stationary fuel cell is economically superior in terms of Total Annual Heating Costs are accentuated in blue.

⁸¹ For the decision making situation of the household, we assume that district heating is available in the vicinity of the building, i.e. the street – however, the building is not fully connected yet. Consequently, the homeowner who faces a heating technology choice has to ensure the connection of the building to the district heating grid should he opt for district heating as his preferred solution.

⁸² For district heating prices, we refer to Statista (Germany), the European Commission (Italy), E.On (UK), and euroheat (Poland) as reference sources. Please see also Figure 48.

⁸³ The exemplary calculation considers the use case DE3 in Figure 44.

ID	Gas condensing boiler		Gas condensing boiler and solar thermal		Heat pump (air-to-water)		Heat pump (air-to-water) and PV		Heat pump (ground source)		Internal combustion engine		Stirling engine		District heating	
	As is	10k	As is	10k	As is	10k	As is	10k	As is	10k	As is	10k	As is	10k	As is	10k
DE1	4.7x	0.8x	3.5x	0.6x	1.9x	0.3x	1.7x	0.3x	1.4x	0.3x	1.6x	0.3x	1.7x	0.4x	5.0x	0.9x
DE2	3.5x	0.7x	2.9x	0.6x	1.7x	0.4x	1.5x	0.3x	1.3x	0.3x	1.6x	0.4x	1.7x	0.4x	3.4x	0.8x
DE3	3.2x	0.8x	2.7x	0.7x	1.6x	0.4x	1.5x	0.4x	1.3x	0.3x	1.6x	0.4x	1.7x	0.5x	3.1x	0.8x
DE4	2.5x	0.9x	2.2x	0.8x	1.4x	0.6x	1.3x	0.5x	1.3x	0.5x	1.5x	0.6x	1.6x	0.7x	2.2x	0.9x
UK1	4.6x	0.8x	3.2x	0.6x	2.0x	0.4x	1.7x	0.3x	1.2x	0.2x	1.5x	0.3x	1.6x	0.3x	4.5x	0.8x
UK2	5.0x	0.9x	3.4x	0.6x	2.0x	0.4x	1.8x	0.3x	1.3x	0.2x	1.5x	0.3x	1.7x	0.4x	5.1x	0.9x
UK3	4.3x	0.8x	3.1x	0.6x	1.9x	0.4x	1.7x	0.3x	1.2x	0.3x	1.4x	0.3x	1.6x	0.4x	4.0x	0.8x
UK4	3.5x	0.8x	2.7x	0.6x	1.8x	0.4x	1.6x	0.4x	1.2x	0.3x	1.4x	0.4x	1.6x	0.4x	3.0x	0.7x
IT1	3.6x	0.9x	3.0x	0.8x	3.4x	0.9x	2.6x	0.7x	2.1x	0.6x	1.5x	0.5x	1.7x	0.5x	4.6x	1.2x
IT2	2.7x	0.8x	2.7x	0.8x	3.1x	0.9x	2.4x	0.7x	2.0x	0.6x	1.5x	0.5x	1.7x	0.6x	3.8x	1.2x
IT3	2.4x	0.9x	2.2x	0.8x	2.6x	1.0x	2.2x	0.8x	1.9x	0.8x	1.4x	0.6x	1.6x	0.7x	2.8x	1.1x
IT4	2.2x	0.9x	2.0x	0.9x	1.8x	0.8x	1.7x	0.7x	1.4x	0.7x	1.4x	0.6x	1.5x	0.7x	2.5x	1.1x
PL1	5.3x	1.3x	4.3x	1.1x	2.2x	0.6x	2.0x	0.5x	1.6x	0.5x	1.7x	0.5x	2.1x	0.7x	5.9x	1.5x
PL2	4.5x	1.2x	3.8x	1.1x	2.1x	0.6x	2.0x	0.6x	1.6x	0.5x	1.7x	0.5x	2.1x	0.7x	5.1x	1.5x
PL3	3.9x	1.2x	3.4x	1.0x	2.0x	0.7x	1.9x	0.6x	1.6x	0.6x	1.6x	0.6x	2.0x	0.8x	4.3x	1.4x
PL4	3.5x	1.2x	3.1x	1.0x	2.0x	0.7x	1.8x	0.7x	1.6x	0.6x	1.6x	0.6x	2.0x	0.8x	3.8x	1.4x

Calculation from Patchy Progress scenario

Figure 51: Economic benchmarking results across all residential use cases in terms of multiples⁸⁵

Figure 51 displays several important findings. The conventional boiler and district heating are currently the most inexpensive solutions in all use cases. The fuel cell's cost gap to the competing heating appliances is usually smallest in houses with lower energy efficiency standards, i.e. non- or partially renovated buildings. This becomes particularly clear from Figure 52 which displays the annual heating cost on a per kWh basis. Boilers are comparatively cheap in the UK and in Poland, and heat pumps are somewhat less expensive in Italy and Poland. Given the outlook on higher production volumes in Figure 51, the stationary fuel cell can overtake the heat pump economically. Given that the

⁸⁴ Units refer to cumulative production volume of generic fuel cell mCHP per manufacturer as main driver for cost reduction.

⁸⁵ The table displays the ratio of the total annual heating costs of the generic fuel cells divided by the total annual heating costs of the respective competing technology. The colour code indicates whether or not the fuel cell is more expensive than the alternative. Blue shading reflects superior economic performance of the generic fuel cell systems. For future energy price developments, we consider the Patchy Progress scenario.

cost gap to the heat pump is somewhat wider in Italy, the direct competition from the former is greater in this market. Furthermore, the cheap and far-reaching availability of district heating in Poland makes it a difficult market for stationary appliances in general. We consider Germany and the UK to be the most competitive markets at present. Germany accommodates a wide array of heating technologies. The respective cost advantages over the fuel cell are not as prominent in this market as in the other focus countries. Moreover, although gas boilers are highly cost competitive in the UK, the fuel cell is expected to catch up with sufficient production volumes per company (see Figure 51). Given probably no cost reductions on the boiler side and a very high penetration of the gas network, the UK is a very attractive market for the fuel cell.

Figure 52 shows the annual cost per kWh for different heating systems at current state of development. The most economically progressive figures are accentuated by colour code.

ID	Gas condensing boiler	Gas condensing boiler and solar thermal	Heat pump (air-to-water)	Heat pump (air-to-water) and PV	Heat pump (ground source)	Internal combustion engine	Stirling engine	District heating	Fuel cell CHP
DE1	0.10	0.13	0.25	0.28	0.34	0.29	0.28	0.09	0.47
DE2	0.09	0.10	0.18	0.20	0.23	0.19	0.18	0.09	0.30
DE3	0.08	0.10	0.16	0.18	0.20	0.17	0.16	0.09	0.26
DE4	0.07	0.08	0.12	0.13	0.14	0.12	0.11	0.08	0.18
UK1	0.09	0.13	0.22	0.25	0.35	0.29	0.26	0.10	0.43
UK2	0.10	0.15	0.24	0.28	0.40	0.34	0.30	0.10	0.50
UK3	0.09	0.12	0.20	0.22	0.31	0.27	0.23	0.09	0.38
UK4	0.08	0.10	0.15	0.17	0.22	0.20	0.17	0.09	0.27
IT1	0.11	0.14	0.12	0.16	0.20	0.27	0.24	0.09	0.41
IT2	0.11	0.12	0.11	0.14	0.16	0.22	0.20	0.09	0.33
IT3	0.10	0.11	0.09	0.11	0.12	0.16	0.15	0.08	0.24
IT4	0.10	0.10	0.12	0.12	0.15	0.15	0.14	0.08	0.21
PL1	0.05	0.07	0.13	0.14	0.17	0.17	0.13	0.05	0.28
PL2	0.05	0.06	0.11	0.12	0.14	0.14	0.11	0.05	0.23
PL3	0.05	0.06	0.09	0.10	0.12	0.12	0.09	0.04	0.19
PL4	0.05	0.05	0.08	0.09	0.10	0.11	0.08	0.04	0.17

Figure 52: Economic benchmarking across all residential use cases in terms of levelised cost of heating [EUR/kWh_{th}]⁸⁶

Industry experts project substantial cost reductions given that sufficiently extensive economies of scale can be realised. The corresponding units needed to achieve cost reductions are displayed in Figure 53. Whereas the current situation is depicted in Figure 51, Figure 53 also displays the potential cost reductions on a per kWh basis. Heat pumps, an arguably expensive technology in comparison with conventional boilers, could be outperformed within only a few years. Becoming competitive with the conventional gas boiler, would require a ca. 80% cost reduction.

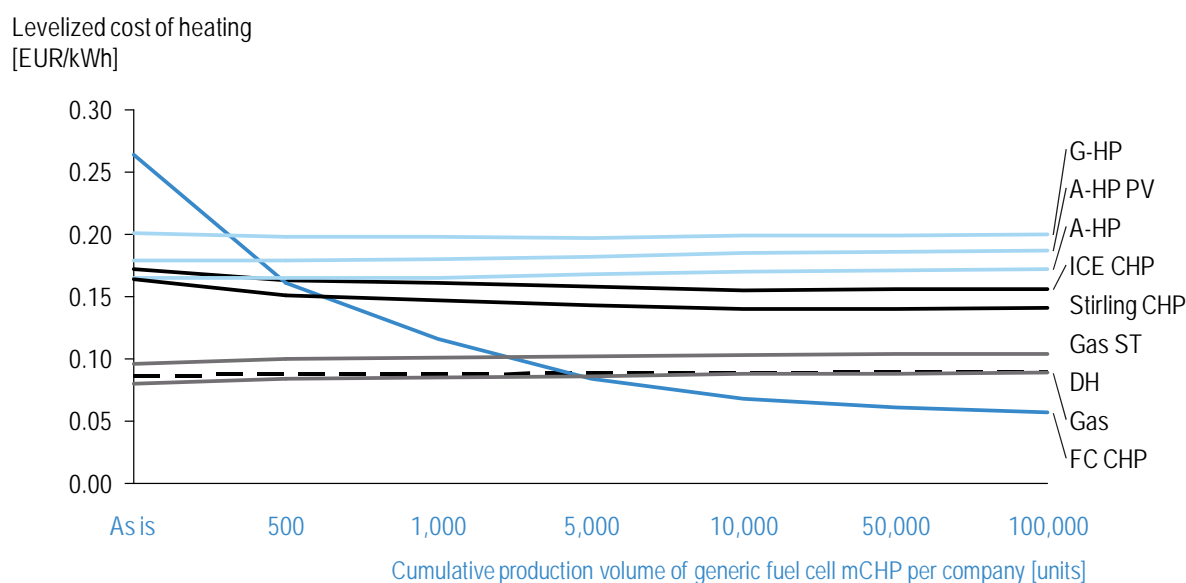


Figure 53: Future development of levelised cost of heating for a partially renovated German 1/2-family dwelling⁸⁷

Environmental performance: The ecological footprint of the fuel cell system

The favourable environmental performance is a key advantage of the fuel cell system compared to other heating solutions. It outperforms conventional applications substantially in terms of emissions of greenhouse gases, pollutants and particulates – even if the conventional technologies are combined with renewable solutions such as solar thermal or PV. This is true for both the emission of greenhouse gases, as well as pollutants and particulates. Whereas the conventional boiler has the most unfavourable CO₂ emissions balance, the heat pump is particularly unattractive in terms of pollutants such as NO_x. Even more so, as visualised in Figure 54, the FC emission savings through auto-generation of electricity are so substantial that the NO_x balance becomes negative.

⁸⁶ Blue shading emphasises the least expensive heating solutions. Calculations based on status-quo technology development and the Patchy Progress scenario.

⁸⁷ The calculation considers the use case DE3 in Figure 44 and the Patchy Progress scenario. For comparability with energy price developments and cost-down potential of competing technology, we assume an underlying timeline for the volume uptake of the generic fuel cell.

1-family dwelling – Renovated



Munich

> Construction year:	1964
> Heated living space:	103 m ²
> Residents:	4
> Annual heat demand:	178 kWh/m ²
> Annual warm water demand:	786 kWh/p
> Total annual heat demand:	21,438 kWh
> Maximum heat load:	17 kW
> Total annual power demand:	5,200 kWh

Patchy Progress scenario

Total annual emissions

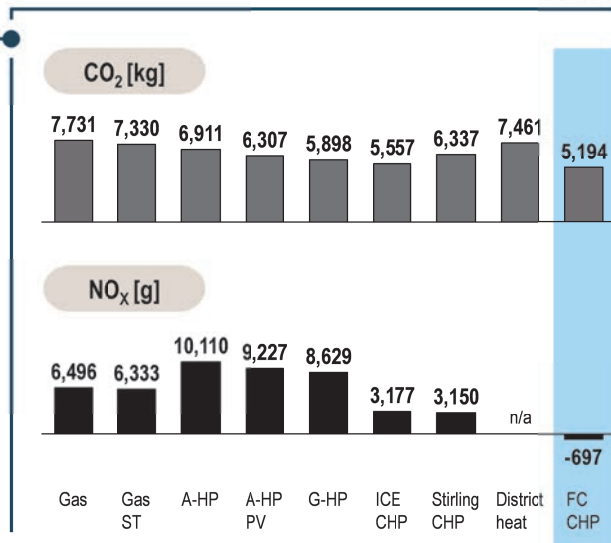


Figure 54: Environmental benchmarking in a German partially renovated, 1/2-family dwelling⁸⁸

It is important to mention that – for power-driven, add-on fuel cell CHPs with electrical efficiencies of 60% and more that run in base-load mode for almost the entire year – CO₂ emissions are even larger. This is due to the longer operating hours and the even larger substitution of grid power supply as well as substantial power feed-in.

The environmental benchmark relies on three components, the fuel consumption of the heating technology, the attributed emissions from grid electricity consumption, and emissions savings through electricity production. This calculation is visualised in Figure 54 for the fuel cell system in the DE3 case.

Excursus and recap: Underlying emission factors

The emissions from power consumption are calculated from the power mix of the four focus countries, which are displayed in Figure 55. In a direct comparison with fossil energy sources, natural gas is comparatively clean. This implies that power generation using gas is cleaner than fossil alternatives. In spite of European-wide deployment of renewable technologies, the emissions of a single kWh of electricity is still higher than the gas benchmark in all four focus countries. This is equally true for pollutants as Figure 55 makes extraordinarily clear.

⁸⁸ The calculation considers the use case DE3 in Figure 44

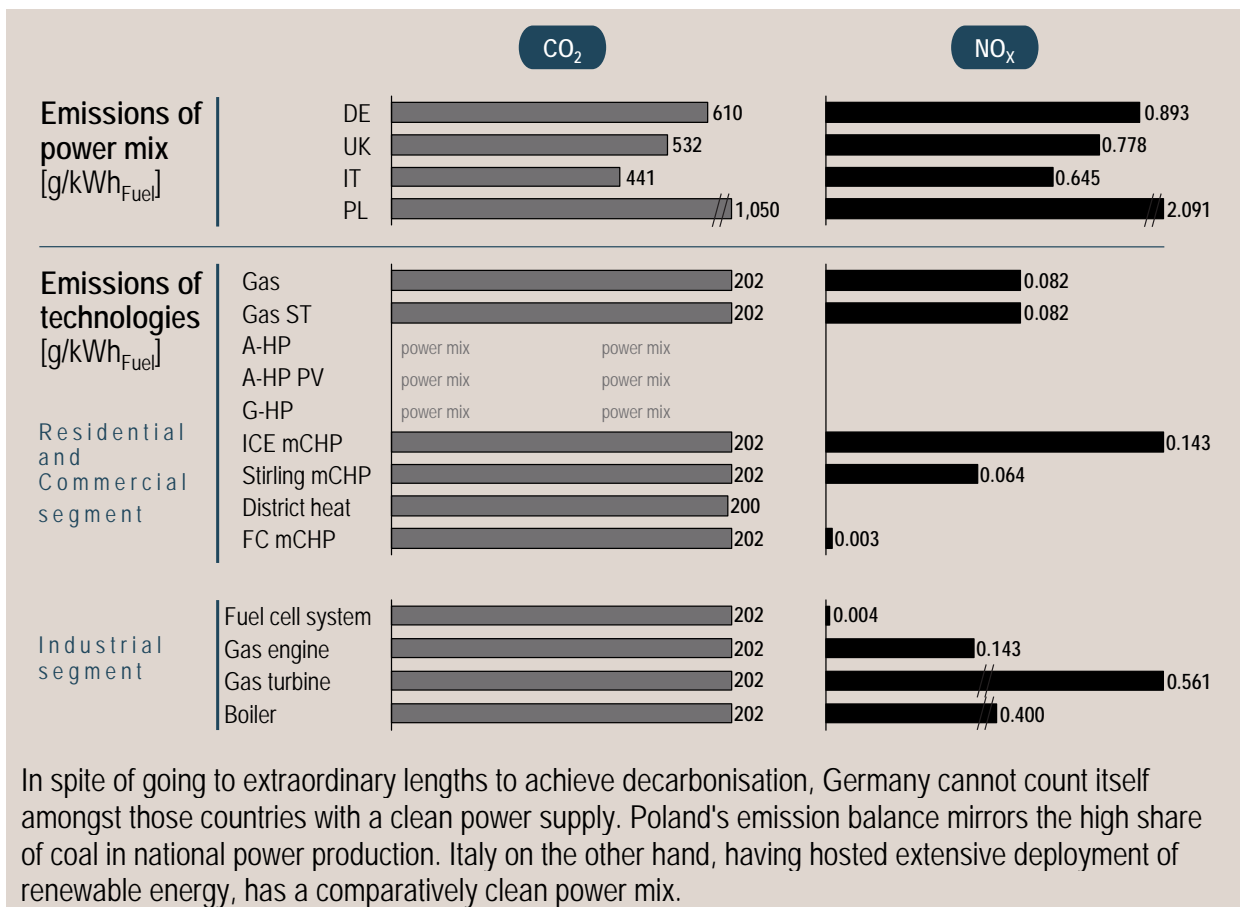


Figure 55: Power generation mixes and technology emission factors for the four focus markets as of 2014⁸⁹

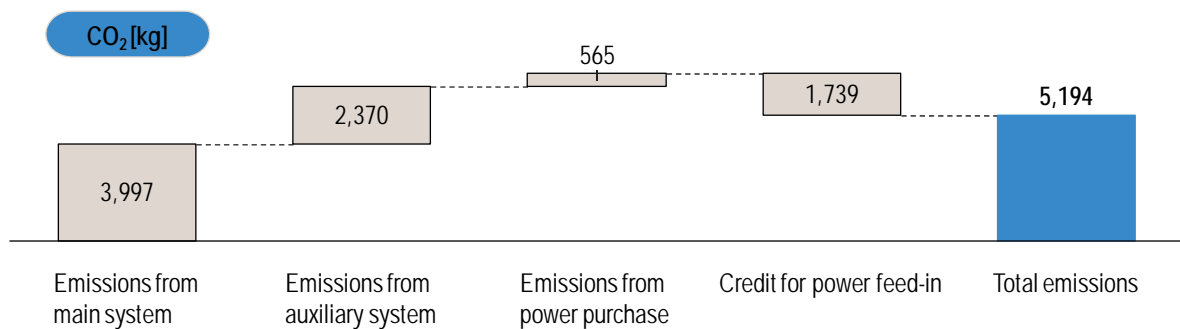


Figure 56: Calculation of total attributable, annual CO₂ emissions for the generic fuel cell mCHP [kg]⁹⁰

To calculate and compare the annual emissions of each technology, the fuel input is multiplied with the corresponding value for emissions. The conventional boiler produces 4,558 kg in the DE3 case, given an annual production of 21,438 kWh heat. The additional emissions resulting from power

⁸⁹ Cf. Umweltbundesamt (2013), Royal Dutch Shell (2013), IEA (2014), IFEU (2012). CO₂ emissions from district heating is fully dependent on the heat source mix, the figure here represents an average as per Royal Dutch Shell (2013)

⁹⁰ The calculation considers the use case DE3 in Figure 44 as per the power-credit or total-balance methodology

consumption of 5,200 kWh amount to 3,172 kg. Equivalent calculations are performed for NO_x emissions using the data in Figure 55. The calculation of the fuel input was equivalent to the calculation of fuel costs outlined in the section above.

ID	Gas condensing boiler	Gas condensing boiler and solar thermal	Heat pump (air-to-water)	Heat pump (air-to-water) and PV	Heat pump (ground source)	Internal combustion engine	Stirling engine	District heating
DE1	61%	66%	66%	73%	73%	87%	70%	63%
DE2	64%	68%	71%	77%	82%	91%	77%	66%
DE3	67%	71%	75%	82%	88%	93%	82%	70%
DE4	82%	85%	94%	99%	115%	104%	103%	85%
UK1	67%	70%	77%	85%	86%	91%	75%	69%
UK2	69%	73%	79%	88%	87%	85%	77%	71%
UK3	69%	72%	80%	88%	90%	84%	78%	71%
UK4	73%	76%	88%	94%	102%	85%	85%	76%
IT1	73%	79%	100%	117%	103%	93%	82%	76%
IT2	75%	81%	106%	120%	111%	92%	85%	78%
IT3	81%	85%	122%	134%	129%	99%	94%	85%
IT4	84%	88%	123%	135%	152%	96%	96%	88%
PL1	18%	18%	14%	16%	17%	39%	29%	18%
PL2	28%	29%	22%	24%	28%	52%	49%	29%
PL3	39%	40%	30%	32%	38%	68%	71%	40%
PL4	45%	46%	34%	37%	44%	67%	81%	47%

Figure 57: Environmental benchmarking across all residential use cases in terms of total attributable annual CO₂ emissions⁹¹

The results of the emissions benchmarking are displayed in Figure 57. For each use case the fuel cell emissions are shown as a percentage of the emissions from competing technologies. The cases where the stationary fuel cell has a superior environmental performance are highlighted by colour code. Two main drivers of a building's emissions balance stand out: Firstly, the emissions savings in use cases with a low heat demand are comparatively greater. Secondly, the national power mix emissions determine to what extent fuel cell power production from gas is attractive. Unequivocally, the greatest

⁹¹ The table displays the ratio of the total attributable annual CO₂ emissions of the generic fuel cells divided by the total attributable annual CO₂ emissions of the respective competing technology. Blue shading reflects superior performance of the generic fuel cell systems

emissions savings potential is in countries with high emissions per kWh of electricity. For this reason heat pumps account for greater emissions in countries with high emissions from the power mix. The fuel cell has a clear advantage here. However, the Italian case demonstrates that a cleaner power mix can take the fuel cell's superior position. The fuel cell is the most carbon-efficient CHP technology.

Other factors: Further benefits of the fuel cell system

Regarding the physical compactness of the stationary fuel cell, it does not rank behind most alternative heating appliances – as such it tends to be a non-invasive technology for 1/2-family dwellings. Only Stirling engine and conventional boiler require significantly less surface area. However, the fuel cell is more pleasant than all alternatives in terms of **noise**. The application is 20% less noisy than the combustion engine, and 5-10% less noisy than any other benchmark technology.

Sensitivities: External factors driving the benchmark

The fuel cell has a clear emissions advantage over its competitors. This is particularly true for countries highly relying on fossil fuels their power supply, such as Poland because CHP from gas is comparatively carbon-efficient. Therefore, the fuel cell is more environmentally friendly than the gas boiler, even if solar thermal collectors contribute to the heat production. Given high emissions from the power mix, the heat pump currently doesn't match the fuel cell's potential. Consequently, fuel cells could reduce greenhouse gases, pollutants and particulates resulting from residential sector energy demand significantly. However, the sensitivities require careful attention. A 1% reduction in CO₂ emissions in the power mix diminishes the advantage over the boiler by more than 1% in all focus markets. The effect is even greater for the heat pump, whose emission balance benefits even more directly from a clean power mix. Countries already moving rapidly towards decarbonised electricity production such as Italy, Spain and Ireland would benefit increasingly less from residential CHP over time. Figure 58 depicts an overview of what level of emissions would be necessary for the fuel cell to be outperformed.

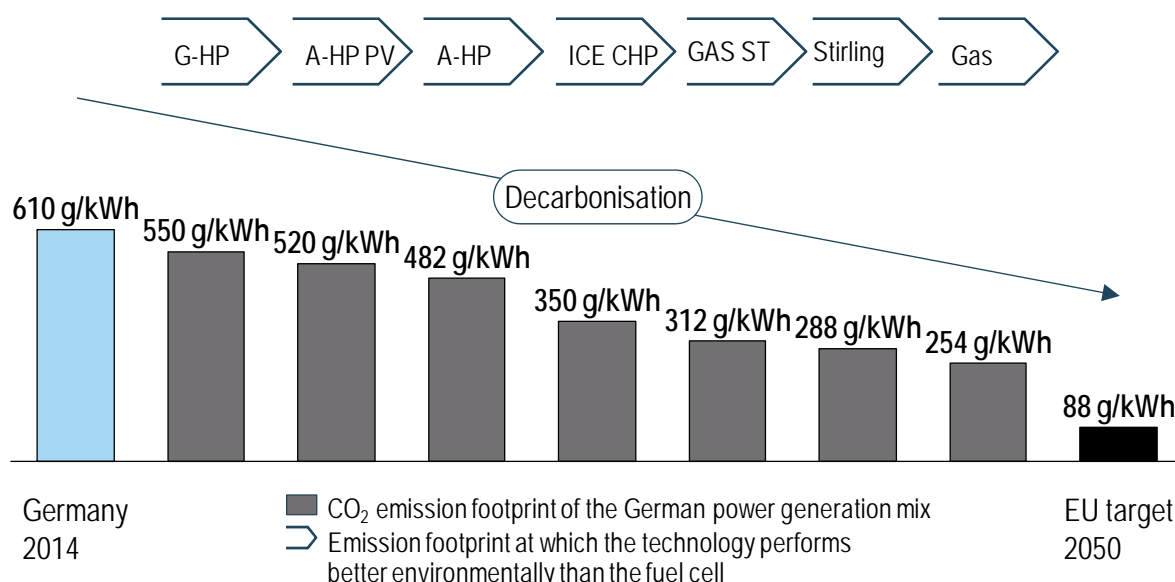


Figure 58: Decarbonisation milestones for German power generation mix according to the competitiveness of the generic fuel cell mCHP vis-à-vis competing conventional technologies⁹²

The EU emissions target for 2050 is referenced in Figure 58 to provide an idea of the extent to which the EU aspires to decarbonise the European energy mix. The emissions savings that can be realised through the fuel cell depend crucially on the reduction of grid power consumed. If the grid becomes more carbon-efficient, this effect diminishes. Figure 58 displays the power-mix emissions factors that would be necessary for the respective competing technologies to outperform the fuel cell in the DE3 use case. At only 482 g/kWh of CO₂ footprint in the German power mix, the air-to-water heat pump would have a better CO₂ balance than the fuel cell in this specific use case.

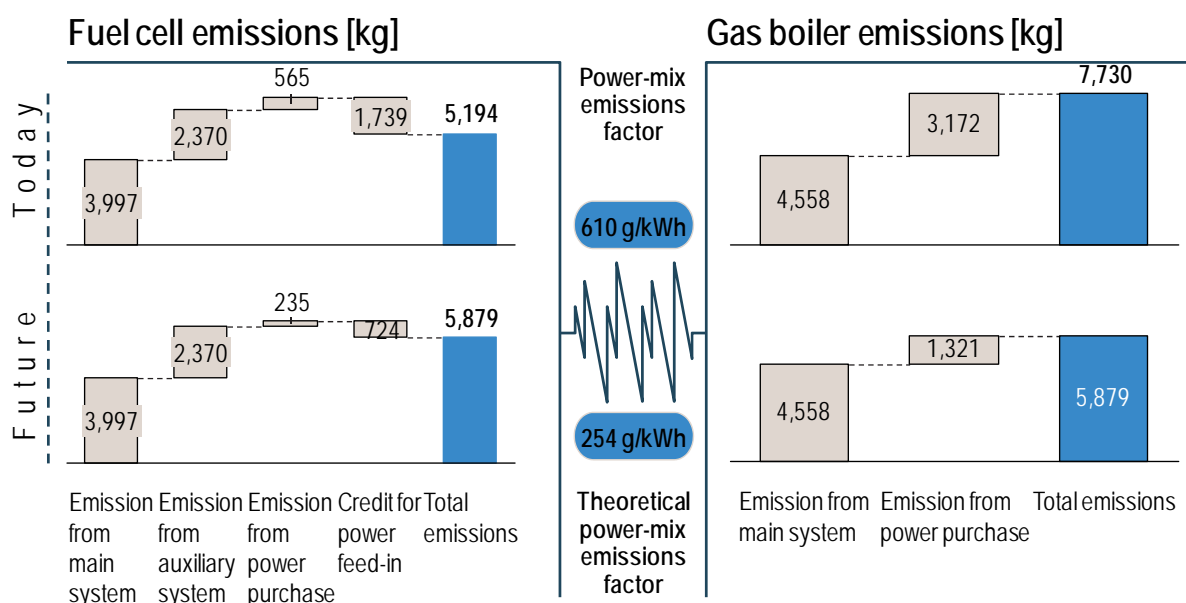


Figure 59: Example for environmental benchmarking of the generic fuel cell mCHP with a condensing boiler under the current emissions footprint and the hypothetical break-even footprint of the German power mix⁹³

The power mix is a crucial determinant of the environmental performance of the fuel cell. This is primarily due to the fact that the energy savings attributable to the fuel cell through power generation mitigate the greater gas requirements for heat production. Decarbonisation slowly does away with this advantage. These dynamics are depicted in Figure 58 for the DE3 case, by assuming a theoretical power mix emissions factor of 254 g/kWh power.

The spark spread is a crucial driver of the fuel cell's economic competitiveness. A high electricity price coupled with a low gas price can reduce OPEX substantially. The analysis within the distributed systems scenario made it clear that fuel costs represented a minor fraction of the total cost of the system in 2014 and are negligible in comparison to the fuel expenses for other technologies. Non-CHP gas-based technologies are consistently outperformed. In the Patchy Progress scenario, heat pumps also have significantly higher fuel costs than CHP technologies in general and the fuel cell in particular. However, the sensitivities are delicate. An unfavourable gas price development, combined with modest

⁹² Should the emissions footprint of the German power generation mix fall below 350 g/kWh, the generic fuel cell mCHP (with status-quo efficiencies) loses its competitive edge over the ICE CHP in terms of total attributable annual CO₂ emissions. The calculation considers the use case DE3 in Figure 44, i.e. a German partially renovated, 1/2-family dwelling

⁹³ The calculation considers the use case DE3 in Figure 44, i.e. a German partially renovated, 1/2-family dwelling

electricity price increases would benefit the heat pump at the expense of the fuel cell, as the Untapped Potential scenario suggests. Countries with low electricity prices such as Poland and France are notably unattractive in this respect. The importance of the spark spread is visualised in Figure 60 for the DE3 use case, where the fuel cost gap to the conventional boiler and the air-to-water heat pump is depicted. The highly profitable spark spread assumed in the distributed systems scenario further opens the gap to the fuel costs for the competing technologies.

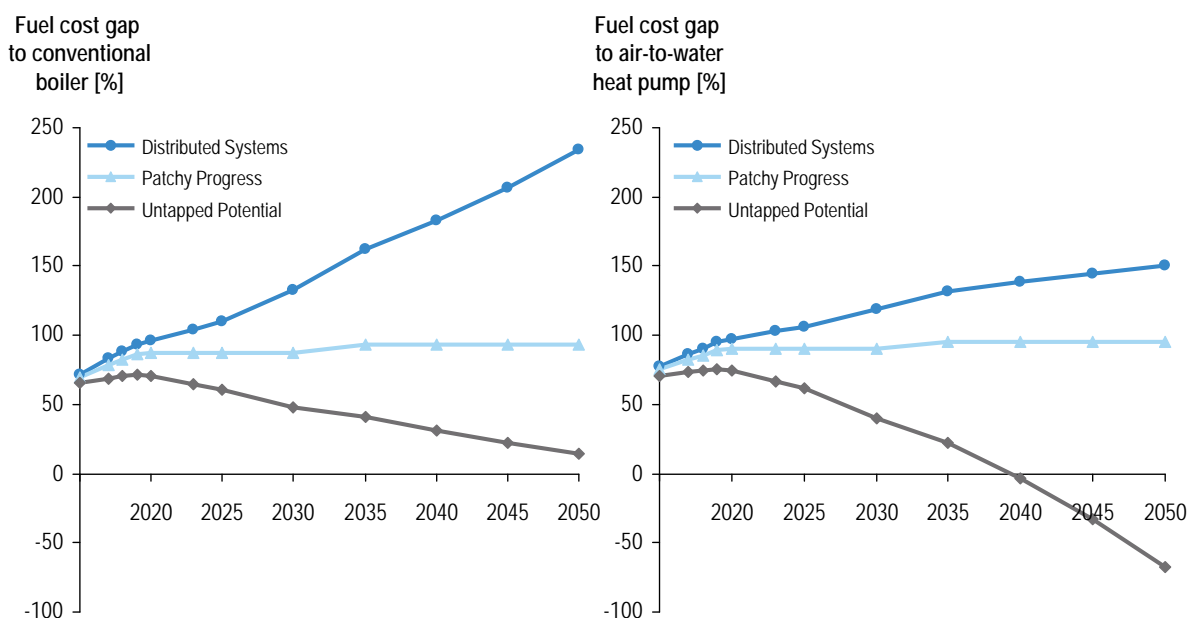


Figure 60: Sensitivity analysis of economic benchmarking in different scenarios of energy price developments⁹⁴

Summary of findings: Standing and perspective of the stationary fuel cell

Use cases with high heat demand are more attractive for the fuel cell than others. This is because long runtime hours allow for extensive electricity production, which is either remunerated or saved, **given a profitable spark spread**. As heating requirements in the residential sector decline through the implementation of energy efficiency measures such as advanced building insulation, the intrinsic advantage of CHP is not extensively appreciated.

High CAPEX is currently the greatest impediment to the successful diffusion of stationary fuel cell heating systems. To achieve progressive market penetration, substantial capital cost reductions are indispensable. Moreover, a 40% system price reduction in the short to medium run would lift the fuel cell to within price range of the ground-to-water heat pump.

The OPEX performance alone is already highly competitive. The fuel cell CHP system has very low fuel costs given the current market prices, which makes it highly attractive. Regarding the maintenance costs, the technology still shows room for improvement if compared to the condensing boiler and the heat pump. However, the maintenance costs are less than 50% of those of the internal combustion engine, and already within a reasonable range of the Stirling. Industry experts expect further reductions.

⁹⁴ The calculation considers the use case DE3 in Figure 44, i.e. a German partially renovated, 1/2-family dwelling

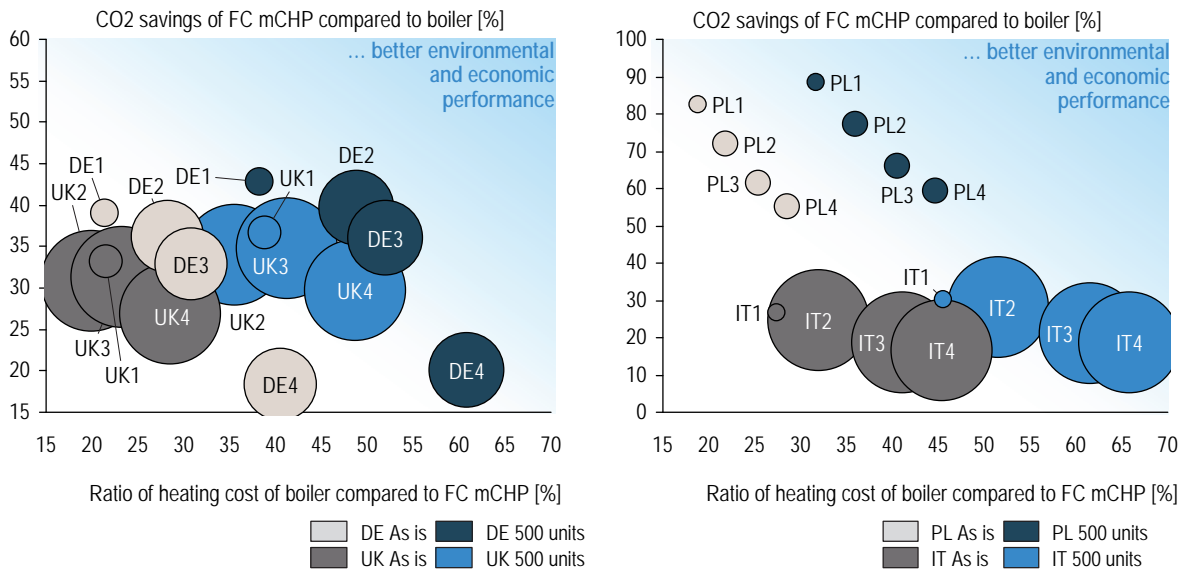


Figure 61: Match of market sizes with economic and environmental benchmarking results across all four focus markets with their residential use cases⁹⁵

Overall, the stationary fuel cell application has great potential as a heating appliance. The most noteworthy immediate benefit can be derived from the significantly lower emissions of greenhouse gases, pollutants and particulates. This makes it an outstanding tool to meet climate goals by reducing the carbon footprint of the residential sector. However, existing efforts to make the power mix more environmentally friendly and energy efficiency measures may jeopardise this competitive advantage in favour of conventional solutions and heat pumps. This possibility can be addressed in time by achieving significant cost reductions and thereby gaining economic leverage over competing technologies. If this is pursued with determination, social benefits beyond the use case can be exploited extensively, paving the way for the successful integration of renewables and the development of a hydrogen-based system.

BOX 2: Power-to-gas and green hydrogen enable long-term success of the fuel cell

The fuel cell represents a significant milestone on the long road to a decarbonised energy supply. Even though the application discussed in the text relies on natural gas, the diffusion of the technology today will enable the switch to hydrogen tomorrow. Furthermore, the rapid diffusion of variable renewable technologies will require additional storage solutions for electricity in order to bridge production gaps and fill in demand shortages whenever necessary. Power-to-gas solutions are a very appropriate solution with regard to this difficulty, given that storage demand is projected to more than triple by 2030 in countries like Germany.

Power-to-gas presents a viable – maybe the only viable – solution to the long-term storage challenge that arises when decarbonising the power mix by considerably expanding generation from intermittent renewable energy sources. Although the conversion efficiency of power-to-gas (i.e. the production of Synthetic Natural Gas (SNG)) is even lower than the conversion to hydrogen, it has the advantage of being complementary to existing natural gas





⁹⁵ Abbreviations refer to use cases in Figure 44. The size of the bubble reflects the size of the primary, addressable market [‘000 units]. For cumulative production of 500 units per company, we assume energy prices in 2017 under the "Patchy Progress" scenario

infrastructure. Injecting SNG gas into the grid does not present a major obstacle to the existing infrastructure for power generation, i.e. gas turbines. Furthermore, fuel cells could serve as technology of choice for power re-generation, once the number of distributed systems is sufficiently high. Given Europe's ambitions to reduce gas imports, the prospect of increasing domestic production with power-to-gas whilst mitigating the storage problem is highly attractive.

Hydrogen is 100% emissions-free when considering direct emissions on site. It can be stored easily and, most importantly, it can be produced through electrolysis, breaking down water molecules into their two components hydrogen and oxygen. Currently, the extensive employment of this technology would have to rely on a polluting power mix to produce clean hydrogen, an unsound compromise. However, an increasing deployment of renewable energy, particularly variable renewables, may do away with this impediment and facilitate the transition to an energy system based on the world's most abundant resource. At first sight it may seem obscure that a technology running on gas is deemed environmentally friendly. However, the direct emissions from the fuel cell are significantly lower than the conventional alternatives as discussed in the text. Furthermore, this advantage may wither away as the power mix becomes cleaner. At first sight this is a disadvantage for the fuel cell. However, a cleaner power mix may also make extensive electrolysis more likely, which in turn benefits the fuel cell. It is precisely this switch from competition with the power mix to complementarity which can bring about the comprehensive decarbonisation of the residential heating segment. Given this outlook, the decision for the fuel cell today and the environmental savings it brings along is also a decision for abundant emission reductions in the future.

Benchmarking commercial segment: Competitive positioning of the fuel cell system

Combined heat and power production from fuel cell systems can help commercial buildings reap significant savings in fuel demand. A steady necessity for heat production, meaning long runtime hours, is the prime enabler of this. Moreover, stationary fuel cell systems can play an important part in reducing the carbon footprint of the commercial sector. It is important to emphasise that – unlike in the case of mCHPs for 1/2-family dwellings – fuel cell CHPs for apartment and commercial buildings have yet to demonstrate their technological readiness through wider demonstration projects and extended field tests. In terms of overall industry maturity, this segment lags behind – but nevertheless has strong potential, as our benchmarking analysis shows.

Description	Decision criteria	Relevance
Economic Performance	<ul style="list-style-type: none"> > Initial investment cost > Total cost of ownership 	
Environmental Performance	<ul style="list-style-type: none"> > Emission performance > Application noise 	
Reliability	<ul style="list-style-type: none"> > Independence from the grid > Uninterrupted power supply > Independence from electricity price movements 	
Other	<ul style="list-style-type: none"> > Physical compactness > Novelty and innovation 	



 Decisive  Irrelevant

Figure 62: Demand-side requirements of decision makers in the commercial market segment

The commercial segment is less easily accessible for innovative, initially expensive non-conventional heating systems than the residential segment. This is primarily due to decision makers assigning higher priorities to the technology's economic performance than to environmental factors and other non-monetised benefits. Decisions in the commercial sector may involve several stakeholders, which increases the complexity of the decision making process. This is particularly true for apartment buildings, where decisions about the extension or renewal of the heating system require multi-party consent, or whenever landlords consider passing a proportion of the costs on to tenants.

ID	Location	Construction year	Renovation work	Share in building stock	Heated space [m ²]	Annual heat demand incl. DHW [kWh]	Power-to-heat demand ratio
DE5	Erfurt (DE)	1965	Yes	41%	867	74,395	42%
DE6	Erfurt (DE)	1965	No	26%	867	155,112	20%
UK5	Nottingham (UK)	1970	Yes	16%	1,100	127,434	20%
UK6	Nottingham (UK)	1970	No	43%	1,100	227,526	11%
IT5	Milan (IT)	1973	Yes	38%	800	76,058	37%
IT6	Milan (IT)	1973	No	34%	800	145,658	19%
PL5	Krakow (PL)	1962	Yes	3%	867	97,262	31%
PL6	Krakow (PL)	1962	No	42%	867	192,555	15%

Figure 63: Apartment buildings defined as use cases⁹⁶

⁹⁶ Cf. Tabula (2012), Verbraucherzentrale NRW (2014), Energy Savings Trust (2014), Roland Berger modelling. To guarantee the suitability of the pre-defined 5 kW_{el} fuel cell CHP in the use cases as central heating technology, we focus on

Apartment buildings are subject to the identical variety of factors determining the heat profile as the dwellings discussed above, namely geographic differences, the degree of renovation, construction year and consumption habits. Representativeness and distinguishability are at the heart of the use case selection, yet comparability was important. For this reason, any two use cases from the same country are distinguishable through the extent of renovation. This was done primarily to analytically isolate the impact of this factor, and secondly because extensively renovated buildings are an appropriate proxy for new builds, in terms of heat demand. The number of residents in each use case ranged from 22-25 people. The power-to-heat ratios are calculated accordingly. In terms of the heat profile of apartment buildings, it is important to single out the features of multi-family homes not applicable to 1/2-family dwellings. Heating habits amongst residents may differ strongly, in terms of timing and the minimum outside temperature at which the heating is switched on during the day, and over a year. This may imply a smooth heating profile making the case attractive for CHPs. The same characteristic applies to power supply, leaving a greater fraction of the power produced by a CHP for on-site consumption.

Type	Location	Construction year	Renovation work	Share in EU building stock ¹⁾	Heated space [m ²]	Annual heat demand incl. DHW [kWh]	Power-to-heat demand ratio
Hospital	Florence	1980	Yes	2%	14,050	5,300,954	26%
Shopping Centre	Stuttgart	1992	Yes	20%	4,000	388,212	33%
Office Building	Milan	1970	Yes	20%	6,000	477,000	33%

Figure 64: Commercial buildings defined as use cases⁹⁷

Hospitals account for heating requirements ranging from 25-65 kWh/bed on a given day, depending on the climate of the hospital's location, the capacity of the hospital, the scope of the hospital facilities, building age and insulation. To a great extent hospitals depend on steam production for sterilisation and disinfection, but also to support auxiliary services such as laundry and cooking. Furthermore, larger hospitals have proportionately greater heat demands. The exemplary hospital considered above is assumed to have 250 beds and to be equipped according to state-of-the-art medical technology standards.

Office buildings represent a substantial share of the European non-residential building stock and consume considerable amounts of energy. Much of this is electricity, driven primarily by the high intensity of electronic devices in the workspace. Furthermore, heat demand is sometimes limited to the working hours of the day. Although this may limit the runtime hours for a heating appliance, it also means that the power and heating load profiles are neatly aligned, making it attractive for simultaneous heat and power generation.

Shopping centres have less homogeneous heat and power load profiles as well as overall demand structures. A major shopping mall may have significant electricity requirements for lighting, electronic devices and electric heating at local points. Some commercial areas may depend on extensive cooling

older buildings with different degrees of renovation. Smaller, more efficient buildings may be better served by smaller fuel cells

⁹⁷ Based on the European non-residential building stock, ratios based on Buildings Performance Institute Europe

appliances, especially those specialising in the sale of fast moving consumer goods. The building considered above is representative for typical retail centres specialising in durable products, with low electricity requirements for storage and exhibition. All the buildings above are assumed to be renovated. This assumption is hardly arguable in light of very short term refurbishment cycles of non-residential buildings, particularly in the office and retail segment.

Definition of technology pool

For the commercial segment, the technology pool from the residential analysis is complemented to include larger modules. This is relevant to the boiler on the one hand, which can now be scaled to deliver heat to greater use cases using less modules. On the other hand it means additional systems are available to cover peak loads whenever a CHP technology is installed as a main system.

	Unit	Gas conden- sing boiler	Gas conden- sing boiler and solar thermal	Heat pump (air-to- water)	Heat pump (air-to- water) and PV	Heat pump (ground source)	Internal com- bustion engine	District heating	Fuel cell CHP ⁹⁸	Fuel cell CHP
Technical Performance	Thermal capacity of main system [kW _{th}]	<50	<50	-	-	-	12.5	-	4	40
	Electrical capacity of main system [kW _e]	-	-	-	-	-	4.7	-	5	50
	Therm. capacity of auxiliary system [kW _{th}]	-	3.3	-	-	-	45	-	>10	>50
	Electrical capacity range of auxiliary system [kW _e]	-	-	-	1.5	-	-	-	-	-
	Thermal efficiency of main system [%]	95	95	360	360	480	63.8	-	37	32
	Electrical efficiency of main system [%]	-	-	-	-	-	27.6	-	50	53
	Thermal efficiency of auxiliary system [%]	-	40	-	-	-	95	-	95	95
	Electrical efficiency of auxiliary system [%]	-	-	-	16	-	-	-	-	-
Economic Performance ⁹⁹	Total cost of packaged system [EUR]	5,240- 6,056	8,173- 11,300	30,708- 31,780	32,926- 34,883	35,733- 38,333	21,971 25,571	2,600	109,900	895,400
	(A) Cost of system [EUR]	5,000	7,000- 8,000	30,308	32,443- 32,617	34,733	20,571	2,300	-	-

⁹⁸ Industry experts expect the technological characteristics, particularly the efficiencies, to improve over time

⁹⁹ All cost figures are disclosed excluding VAT

	(B) Cost of installation [EUR]	240-1,056	1,173-3,520	400-1,472	493-2,450	1,000-3,600	1,400-5,000	300	-	-
Other	Annual maintenance cost [EUR]	50-200	70-260	50-180	130-470	40-130	900-1,100	80	850	6,000
	Major re-invest (if applicable) [EUR]	-	-	-	-	-	-	-	24,000	135,500
	Lifetime [years]	15	15	15	15	15	15	15	15	15

Figure 65: Competing heating technologies in apartment and commercial buildings

Economic benchmarking: The economics of stationary fuel cells

The calculation methodology described in the sections above is applied to the commercial segment. The consolidated results are displayed in Figure 67. It gives an overview of the total annual heating cost today, as calculated for the UK6 use case.

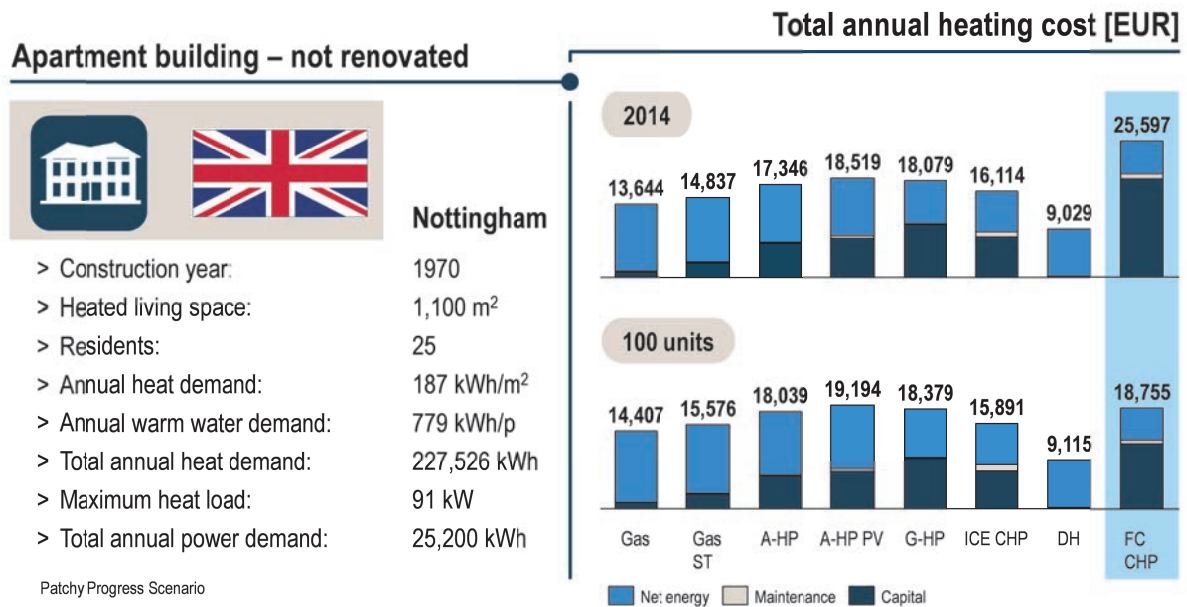


Figure 66: Economic benchmarking in a British non-renovated apartment building¹⁰⁰

The use case overview provided in Figure 66 summarises the **results of an exemplary calculation** for the UK6 use case, a non-renovated apartment building with central heat supply to all dwellings. In terms of annual heating cost, it becomes clear from the 2014 figures that the stationary fuel cell is significantly behind competing technologies. This is almost exclusively due to the higher capital cost, as observed in 2014. In terms of fuel cost, the technology is already highly competitive, given the savings from combined heat and power production.

¹⁰⁰ For our analysis, cumulative production volumes of 100 units per manufacturer are expected by 2019. Energy price developments and cost-down developments for other technologies are considered accordingly under the Patchy Progress scenario. The benchmarking considers the use case UK6 in Figure 63

ID	Gas condensing boiler		Gas condensing boiler and solar thermal		Heat pump (air-to-water)		Heat pump (air-to-water) and PV		Heat pump (ground source)		Internal combustion engine		District heating	
	As is	5,000	As is	5,000	As is	5,000	As is	5,000	As is	5,000	As is	5,000	As is	5,000
DE5	3.0x	0.6x	2.5x	0.6x	1.2x	0.3x	1.1x	0.3x	1.2x	0.3x	1.7x	0.4x	3.2x	0.8x
DE6	2.2x	0.7x	2.1x	0.7x	1.4x	0.5x	1.4x	0.5x	1.6x	0.6x	1.9x	0.8x	1.9x	0.7x
UK5	2.6x	0.8x	2.5x	0.8x	2.7x	0.6x	2.5x	0.5x	2.9x	0.5x	2.8x	0.6x	3.8x	1.4x
UK6	1.8x	0.9x	1.7x	0.9x	1.5x	1.0x	1.4x	0.9x	1.4x	1.0x	1.6x	0.9x	2.8x	1.2x
IT5	2.7x	1.0x	2.3x	1.0x	1.5x	0.7x	1.4x	0.6x	1.4x	0.6x	1.6x	0.7x	3.7x	1.4x
IT6	2.1x	0.9x	2.0x	0.9x	2.1x	0.6x	1.9x	0.5x	2.2x	0.6x	1.8x	0.7x	2.4x	1.3x
PL5	4.1x	0.6x	3.8x	0.6x	2.3x	0.6x	2.2x	0.5x	2.2x	0.6x	2.4x	0.7x	4.9x	0.9x
PL6	2.5x	0.7x	2.2x	0.7x	1.3x	0.6x	1.3x	0.6x	1.3x	0.6x	1.6x	0.7x	3.2x	1.2x
COMM1	1.6x	1.0x	1.4x	0.9x	-	-	-	-	-	-	1.6x	1.1x	1.7x	1.2x
COMM2	5.5x	2.2x	4.6x	1.8x	-	-	-	-	-	-	4.9x	2.1x	4.8x	2.1x
COMM3	3.7x	1.6x	3.4x	1.5x	-	-	-	-	-	-	3.1x	1.4x	4.3x	2.1x

Figure 67: Economic benchmarking across all apartment and commercial use cases in terms of multiples¹⁰²

The fact that the fuel cell is not economically competitive with conventional technologies becomes evident from the Figure 67. The cases where the stationary fuel cell is economically superior are highlighted by colour code. It is also apparent that the cost gap is less obvious in buildings with a very high heat demand such as the non-renovated apartment buildings. Given the magnitude of different heating systems and the variety in heat demands, it is not surprising that the shares of heat coverage by the main heating system varied significantly. Whereas the combustion engine is modulated to cover between 45% and 55% of heat demand, the fuel cell system usually covers a smaller percentage in apartment buildings, so as to keep a lid on the capital costs. Given the use case specific heat profile and the corresponding runtime hours, the power-to-heat ratio is important, as it influences to what extent power is fed into the grid and consumed on site. Given the strong dependency of power supply on working hours, it is assumed that the majority of the electricity is fed into the grid, for the office building and the retail centre.

To some extent, country differences persistently play a role in determining the economic attractiveness of use cases for the fuel cell. High electricity prices benefit the fuel cell in general. For

¹⁰¹ Units refer to cumulative production volume of generic fuel cell mCHP per manufacturer as main driver for cost reduction

¹⁰² The table displays the ratio of the total annual heating costs of the generic fuel cells divided by the total annual heating costs of the respective competing technology. Blue shading reflects superior economic performance of the generic fuel cell systems. For future energy price developments, we consider the Patchy Progress scenario

this reason, Italy and the UK are particularly attractive from an OPEX point of view. Furthermore, if the disparity between feed-in remuneration and power savings through auto-consumption (grid-price) is large, auto-consumption is more attractive than feed-in. Disregarding policy incentives for feed-in, this is the case in Germany. Moreover, the very low figure for the hospital case is one example of this, given the high electricity demand and the convenient congruency of heat and power load distributions and an electricity price gap of 11 EUR ct/kWh, as displayed in Figure 68.

ID	Unit	Gas condensing boiler	Gas condensing boiler and solar thermal	Heat pump (air-to-water)	Heat pump (air-to-water) and PV	Heat pump (ground source)	Internal combustion engine	District heating	Fuel cell CHP
DE5	EUR/kWh	0.09	0.11	0.21	0.23	0.22	0.16	0.08	0.26
DE6	EUR/kWh	0.07	0.07	0.10	0.11	0.09	0.08	0.08	0.15
UK5	EUR/kWh	0.11	0.13	0.20	0.21	0.21	0.18	0.08	0.30
UK6	EUR/kWh	0.09	0.09	0.09	0.10	0.09	0.11	0.08	0.19
IT5	EUR/kWh	0.05	0.05	0.09	0.09	0.10	0.09	0.04	0.21
IT6	EUR/kWh	0.05	0.06	0.10	0.10	0.09	0.08	0.04	0.13
PL5	EUR/kWh	0.06	0.06	0.06	0.06	0.05	0.06	0.04	0.15
PL6	EUR/kWh	0.06	0.07	0.08	0.08	0.08	0.07	0.04	0.11
COMM1	EUR/kWh	0.08	0.09	-	-	-	0.08	0.08	0.13
COMM2	EUR/kWh	0.07	0.08	-	-	-	0.08	0.08	0.35
COMM3	EUR/kWh	0.09	0.10	-	-	-	0.11	0.08	0.32

Figure 68: Economic benchmarking across all apartment and commercial use cases in terms of levelised cost of heating [EUR/kWh_{th}]¹⁰³

Figure 68 displays the total annual heating costs per kWh for apartment buildings and the non-residential buildings considered. The best performing technologies are highlighted by colour code. This representation gives a comprehensive insight into the current situation and the targeted cost reduction to become competitive. This representation makes an easy comparison with current energy prices possible, as displayed Figure 68. It is noteworthy that if per-kWh competitiveness with conventional technologies should be reached, energy price developments will be a crucial driver of the fuel cell technology diffusion. Firstly, the conventional boiler is difficult to outperform economically and requires less fuel input. A highly unfavourable spark spread development could benefit the conventional boiler relatively speaking. This situation would also be significantly advantageous for the heat pump.

¹⁰³ Blue shading reflects superior economic performance of the generic fuel cell systems. For future energy price developments, we consider the Patchy Progress scenario

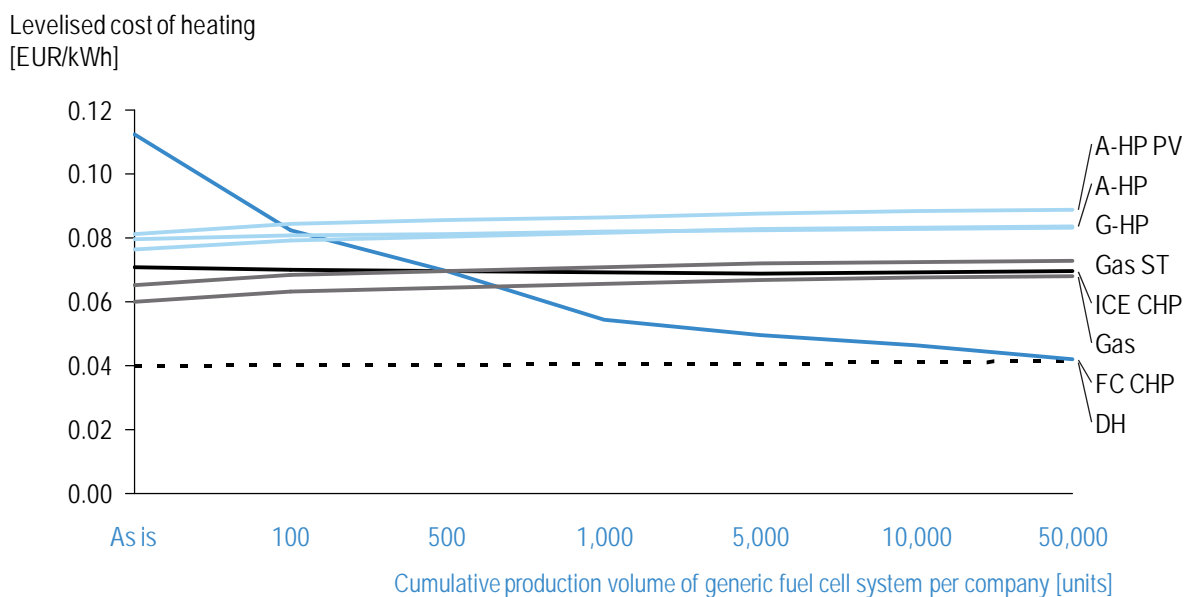


Figure 69: Future development of levelised cost of heating for a non-renovated British apartment building¹⁰⁴

High investment costs are an important hurdle for the fuel cell. Industry experts project considerable capital cost reductions which would reduce the initial investment required of the consumer. These projections for the commercial sector are depicted in Figure 69. If district heating is available, it is the most cost competitive solution for commercial buildings. In order to be cost competitive with the air-to-water heat pump only a ca. 30% cost reduction would be necessary in the UK6 use case. Industry experts expect this to be possible within only a few years. The condensing boiler, however, is ca. 50% less expensive than the fuel cell on a per kWh basis. However, fortunate spark spread developments can somewhat mitigate this effect.¹⁰⁵

Environmental benchmarking: The ecological footprint of the fuel cell system

The results of an emissions calculation for the UK6 use case are displayed in Figure 70. The emissions balance to the left is the result of the interaction of the country specific influences, use case characteristics and the heating technology employed. The benchmarking for this case paints a slightly different picture than the DE3 case discussed above. Primarily, the fuel cell does not match the heat pump in terms of environmental performance, with regard to greenhouse gas emissions. The same is not true, however, for the emission of pollutants such as NO_x. This is a clear advantage of the fuel cell.

¹⁰⁴ The calculation considers the use case UK6 in Figure 63 and the Patchy Progress scenario. For comparability with energy price developments and cost-down potential of competing technology, we assume an underlying timeline for the volume uptake of the generic fuel cell

¹⁰⁵ Please refer to Chapter B for more information

Apartment building – not renovated



Nottingham

- > Construction year: 1970
- > Heated living space: 1,100 m²
- > Residents: 25
- > Annual heat demand: 187 kWh/m²
- > Annual warm water demand: 779 kWh/p
- > Total annual heat demand: 227,526 kWh
- > Maximum heat load: 91 kW
- > Total annual power demand: 25,200 kWh

Total annual emissions

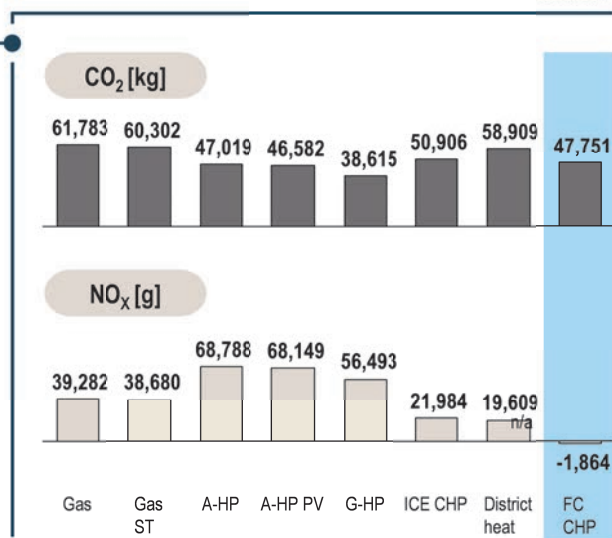


Figure 70: Environmental benchmarking in a British non-renovated apartment building¹⁰⁶

Large buildings could reduce their CO₂ consumption significantly by using fuel cells. The results of the environmental benchmarking are summarised in Figure 70. The cases where the stationary fuel cell has a superior environmental performance are highlighted by colour code. However, the **immediate impact on the environment is not extraordinary**. The environmental benefits are generally more apparent in buildings with lower thermal demand, and hence a smaller thermal peak load which needs to be covered by an additional boiler. In other words, given a single fuel cell the environmental performance is better in a renovated building than in a non-renovated one. This is slightly different for the office building and the shopping centre, given that a significant portion of the power production is being fed into the grid. The difference between the influences the national power mix has on the environmental performance of the fuel cell, becomes remarkably evident from comparing these two use cases. The Germany based office building's performance is significantly better than that of the Italian shopping centre – in spite of the power-to-heat ratios being comparable. This is due to the Italian power mix being significantly cleaner.¹⁰⁷ In countries with a reputedly clean power mix -such as Italy -there appear to be, in fact, environmental disadvantages to employing the fuel cell over the heat pump.

ID	Gas condensing boiler	Gas condensing boiler and solar thermal	Heat pump (air-to-water)	Heat pump (air-to-water) and PV (ground source)	Heat pump (ground source)	Internal combustion engine	District heating
DE5	81%	81%	89%	90%	99%	86%	84%
DE6	86%	87%	98%	99%	115%	93%	89%
UK5	87%	89%	109%	110%	128%	92%	91%

¹⁰⁶ The calculation considers the use case UK6 in Figure 63 and the Patchy Progress scenario

UK6	91%	94%	120%	121%	146%	98%	96%
IT5	94%	94%	122%	124%	139%	96%	97%
IT6	96%	98%	137%	139%	161%	98%	100%
PL5	67%	68%	58%	59%	66%	72%	69%
PL6	72%	73%	59%	59%	70%	97%	74%
COMM1	86%	81%	-	-	-	91%	89%
COMM2	25%	23%	-	-	-	30%	26%
COMM3	61%	60%	-	-	-	69%	63%

Calculation from Patchy Progress scenario

Figure 71: CO₂ emission ratios – commercial segment¹⁰⁸

Other factors: Further benefits of the fuel cell system

An additional prime advantage of the fuel cell is, as in the residential segment, the fact that it is less noisy than the benchmarked alternatives. This may be particularly important to apartment buildings and office buildings. Physical compactness is also relevant in this respect. As outlined above, the fuel cell is generally not behind other conventional technologies in terms of size.

Another key advantage of the fuel cell in the commercial segment is its ability to secure power supply. Particularly office buildings and commercial facilities relying on secure electricity for cooling of non-durable goods would benefit from this. If power-to-gas was applied on a European level more extensively as variable renewables develop a more prominent share in national fuel mixes, fuel cells could play a key role in providing reliable heat and power production for years to come.

Tri-generation of power heat and cooling: SOFC CHPs supply heat at high temperature level (700-800°C or more). This heat could – in principle – be used in summer in adsorption chillers and subsequently supplied to buildings via air conditioning systems. Tri-generation of power, heat and cooling would further increase the runtime of the fuel cell over the year and could further benefit the economic performance of fuel cells compared to conventional CHP technologies.

Sensitivities: External factors driving the benchmark

The fuel cell can reduce the emissions from the commercial sector considerably. As in the residential sector, countries with a significant share of polluting fossil fuels in their power mixes would be the greatest beneficiaries of this technology. However, the gap to the boiler is significant in all countries. The CO₂ savings that can be reaped are significant but not extraordinary.

Saving heat in rented apartments is significantly difficult due to the conflicting interests of landlords and tenants. Whereas tenants would benefit from low fuel costs, landlords may shy away from high investments. On the other hand, the shouldering of energy efficiency measures is subject to the same complications. Given that fuel cells are attractive in buildings with a high heat demand, this may actually prove to be an opportunity, given an appropriate business model to avoid high initial investments.

¹⁰⁸ The colour code indicates whether a value lies above or below the 100% benchmark

With regard to the technology cost, the prime advantage of the fuel cell is the significantly lower net fuel cost, which reduces overall OPEX significantly. Above all, this is driven by the favourable energy prices in Europe, particularly in countries such as Germany. **The spark spread has an important impact on fuel costs.** Directional differences can influence the relative competitiveness to the conventional boiler technology considerably. This is depicted in Figure 72 for the UK6 use case.

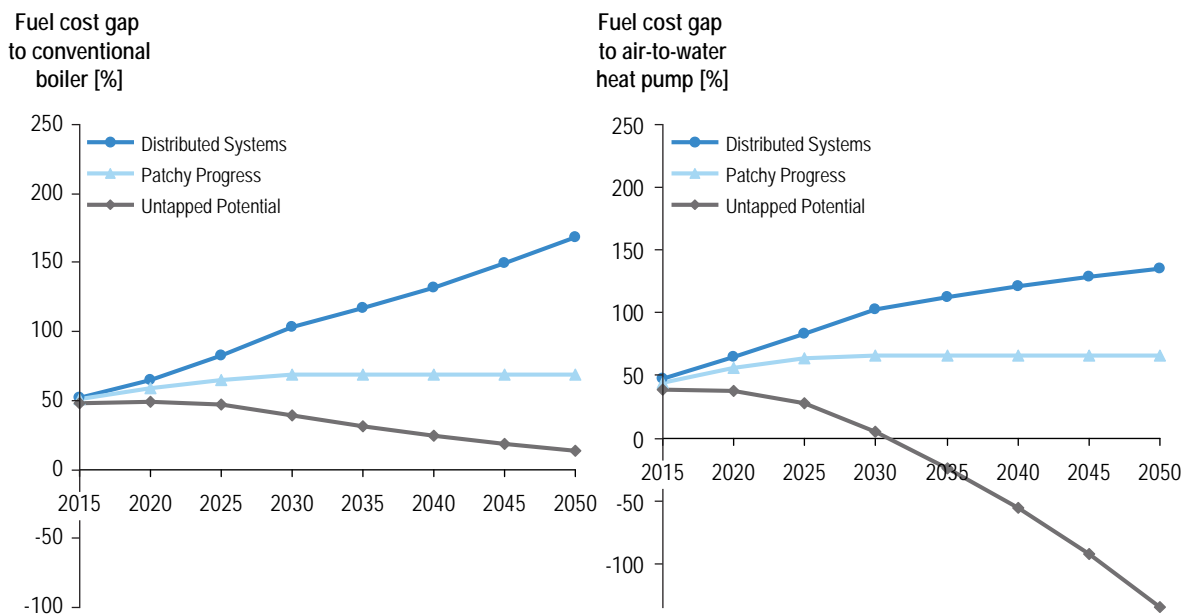


Figure 72: Sensitivity analysis of economic benchmarking in different scenarios of energy price developments¹⁰⁹

The competition from heat pumps as an alternative environmentally attractive technology is much smaller in the commercial sector, given that this technology is limited in its scope. Given that decision chains in the commercial segment are more complex, often involving several stakeholders, the persistence of conventional boilers may prove to be a significant hurdle.

Summary of findings: Standing and perspective of the stationary fuel cell

Overall, the commercial segment presents a high degree of complexity. The segment has great potential for fuel cell systems, especially those buildings with high heat demands that allow for long runtime hours. However, given the high importance of costs in this segment, cost reductions are indispensable to advance market penetration. Given that the OPEX is already very competitive in several European countries, the focus lies on CAPEX reductions before all else. The significant reduction in CO₂ emissions the fuel cell can help bring about is somewhat jeopardised by the impending trend to decarbonisation of the power mix. Therefore, it is very important to achieve cost reductions at an accelerated pace if the technology is to be deployed extensively in the commercial segment. Another key advantage identified for the fuel cell is the significantly lower emission of pollutants such as NO_x. Commercial buildings account for an important share of, particularly urban, air pollution. Extensive deployment may yield significant short-term emissions savings.

¹⁰⁹ The calculation considers the use case DE6 in Figure 63, i.e. a German apartment building

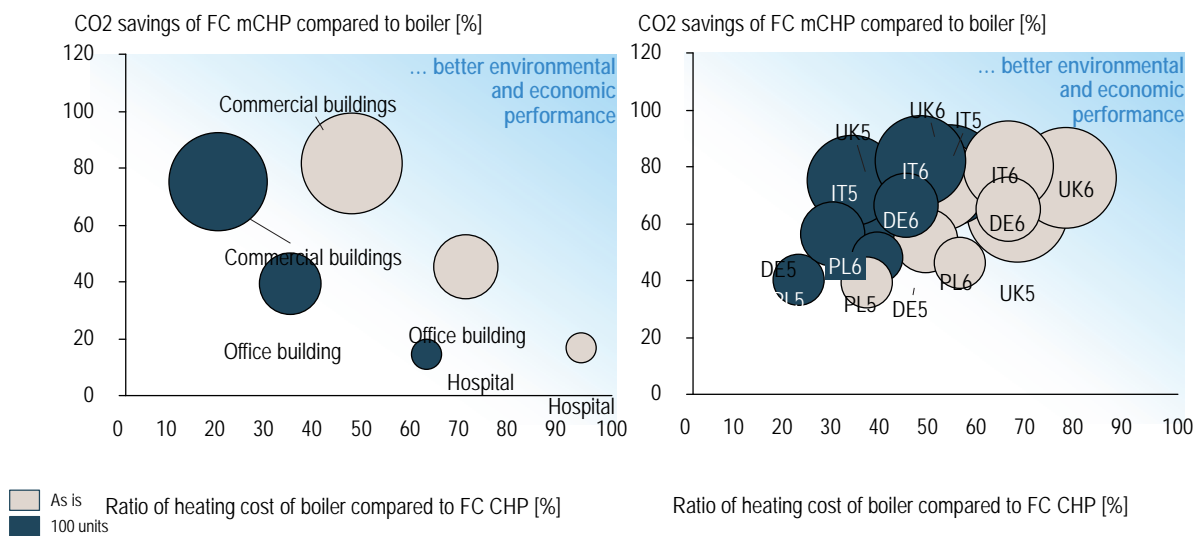


Figure 73: Match of market sizes with economic and environmental benchmarking results across all four focus markets for the apartment and commercial buildings defined as use cases¹¹⁰

Benchmarking industrial segment: Competitive positioning of the fuel cell system

Fuel cell systems can be applied in an industrial context. Both as CHP and prime power solutions, stationary fuel cells are reliable, clean, have long runtimes and require low-frequency maintenance. In some cases, using fuel cell systems can even bypass expensive power supply infrastructure (e.g. data centres) or make use of industrial by-product gases for CHP (e.g. chemical manufacturing). The fuel cell system allows independence from the grid and the associated power prices and outage risks.

Description	Decision criteria	Relevance
Economic Performance	<ul style="list-style-type: none"> > Initial investment cost > Total cost of ownership 	
Environmental Performance	<ul style="list-style-type: none"> > Emission performance > Application noise 	
Reliability	<ul style="list-style-type: none"> > Independence from the grid > Uninterrupted power supply > Independence from electricity price movements 	
Other	<ul style="list-style-type: none"> > Physical compactness > Novelty and innovation 	

Decisive Irrelevant

Figure 74: Demand-side requirements of decision makers in the industrial market segment

¹¹⁰ Abbreviations refer to use cases in Figure 63. The size of the bubble reflects the size of the primary, addressable market. For cumulative production of 100 units per company, we assume energy prices in 2019 under the Patchy Progress scenario.

Figure 74 highlights the key decision criteria for industrial stakeholders and illustrates that the industrial sector tends to be highly price sensitive – the most important criteria are initial investment costs and total cost of ownership. Further criteria such as reliable power supply and the environmental footprint are also relevant, particularly when they have a monetary impact.¹¹¹ The decision making process itself is often relatively complex involving several parties (e.g. energy management, production management, facility management, etc.). Detailed cost and performance analysis is usually required to account for specific use case characteristics and several hierarchical levels.

Within the scope of this study we perform a deep-dive analysis into five applications for fuel cell technologies: data centres, pharmaceutical production facilities, chemical production facilities, breweries and wastewater treatment facilities. In order to tackle the heterogeneous structure of the previously mentioned facility types, we follow a use case approach in which one specific use case is outlined in detail and considered representative for a larger, strongly heterogeneous cluster.

The use cases are country specific, including detailed inputs on national energy prices, electricity generation mixes and the corresponding emissions factors, as well as policy support schemes for CHP production. Given the homogeneity of production processes within countries, the operational characteristics can be generalised.

Annual figures (unless otherwise specified)	Unit	Data centre	Pharmaceutical production facility	Chemical production facility	Brewery	Wastewater treatment facility
Technology type	n/a	Prime power	CHP	CHP	CHP	CHP
Heat demand	MWh	0	11,651	29,127	6,658	2,365
Power demand	MWh	8,000	11,651	11,651	3,329	3,154
Power fluctuation	%	70-100	n/a	n/a	n/a	Constant
Operating time/year	hours	8,760	8,760	8,760	8,760	8,760
Biogas emissions	m ³	0	0	2,000,000	1,000,000	2,000,000
Gas connection available	n/a	yes	yes	yes	yes	yes
Maximum heat load	kW _{th}	0	1,116	1,116	315	315
Maximum power load	kW _{el}	1,000	1,400	1,400	400	400
Temperature required	°C	n/a	130-140	> 130	90-110	60-130
Power feed-in possibility	n/a	yes	yes	yes	yes	yes
Additional specific requirements	n/a	n/a	n/a	n/a	Biogas purification	Biogas purification

Figure 75: Industrial sites and applications defined as use cases

In the case of pharmaceutical production facilities, chemical production facilities and breweries, the fuel cell system only covers the power base load. The data provided in the "power demand" line item of

¹¹¹ For a detailed exploration of the topic, please refer to Box 3

Figure 75 thus refers to the base-load power demand and not total power demand. "Power fluctuation" also refers to the base load of the industries previously described.

The **data centre** use case is particularly power-driven. Currently, power demand fluctuates between 70-100%, however this range is expected to increase as servers and cooling systems become more efficient (i.e. to a probable 30-100% fluctuation). Data centres have a 24/7 operation time and typically use UPS units and generators for back-up power. Power security is highly important in the light of the magnitude of the associated costs, especially for financial services, cloud services, telecommunications, etc. As mentioned in Chapter D, the fuel cell system can bypass back-up costs by using the power grid as back-up. The data centre use case is thus representative for other use cases where the generation of heat is not necessary and in which power security is crucial.

Pharmaceutical companies require large amounts of energy (power and heat) in both research and production facilities. Thermal energy is particularly important in reactors, sterilisers, digesters and mixers, whilst electricity is necessary for production machinery, control systems and measurement equipment. Power security thus plays a highly important role. With regard to heating requirements, sterilisation processes, for example, can require up to 140°C. Digestion processes are also highly heat intensive. However no significant amounts of biogas or hydrogen which could be utilised by fuel cell systems are produced in the processes.

Chemical production facilities are highly power intensive and highly heat intensive. Our selected use case generates hydrogen as a by-product, which is fed into the stationary fuel cell system when not used in the chemical production process (e.g. ammonia production). The power generated can be used on site or fed into the power grid, whereby the industry benefits from additional revenues and emissions credits. Chemical production facilities use hydrocarbons (petroleum, natural gas, etc.) to produce fertilisers, caustic soda, paints, plastic, etc. and use industrial steam of more than 130°C.

As for **breweries**, operation time is a particularly relevant factor. Most breweries operate on a 24/5 basis, applying three shifts, five days a week. During the weekend no brewing is performed, meaning that the heat demand is almost non-existent and the power demand decreases significantly. Heat demand exceeds power demand (in kWh comparison) by 100-200% given vast areas of applicability. Heat is essential in the brewing and glass purification processes and is also used for (storage) buildings heating. The heat demand is evenly split amongst the three applications. The wastewater generated in the brewing process enables biogas generation through anaerobic digestion. The latter is generated 24/7, which means that during the weekend, when there is little power demand, a CHP system could feed the generated power into the grid.

Wastewater treatment facilities have a fairly constant demand for power and heat, operating with limited interruptions. Heat is mostly and extensively used for the dehumidification of sewage sludge. The required heat temperature may reach up to 130°C. Up to 24 litres of biogas per population equivalent can be gained by applying anaerobic digestion on the wastewater. The chosen use case utilises the produced biogas with a volume of 2 million m³ to cover approximately 50% of its energy requirements. The wastewater treatment facility used for the benchmarking exercise is connected to both the gas network (for natural gas supply) as well as the power network (for potential feed-in).

Definition of technology pool

For the industrial segment we included the most common CHP solutions in the industrial segment (i.e. the gas combustion engine and the gas turbine) as well as the grid/boiler combination suited to the specific use case requirements.

For the prime power use case the fuel cell only competes against the grid, as heat is not required. In the large natural gas CHP cluster for pharmaceuticals and chemicals, the competing technologies are the

large > 1,400 kW_{el} gas combustion engine and gas turbine, as well as grid and boiler. The smaller 400 kW_{el} combustion engine and gas turbine fit the biogas CHP cluster for breweries and wastewater treatment facilities.

In Figure 76 the characteristics of all competing technologies are illustrated.

	Unit	Gas turbine 500 kW _{el}	Gas turbine 1.4 MW _{el}	Gas comb. engine CHP 400 kW _{el}	Gas comb. engine CHP 1.5 MW _{el}	Gas cond. boiler 300 kW _{th}	Gas cond. boiler 1.5 MW _{th}	Fuel cell system 400 kW _{el}	Fuel cell system 1.4 MW _e
Technical Performance	Electrical capacity [kW _{el}]	500	1,400	400	1,495	-	-	400	1,425
	Thermal capacity [kW _{th}]	1250	2,940	549	1,770	297	1,484	315	1,116
	Electrical efficiency [%]	20	28	38	40	-	-	46	49
	Thermal efficiency [%]	51	50	54	48	95	95	35	31
	Availability [%]	100	100	100	100	100	100	100	100
	Fuel [text]	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas
Economic Performance	Total cost of packaged system [EUR]	1,165,000	2,315,000	949,000	1,861,000	23,370	105,088	2,403,813	6,558,425
	(A) Cost of system [EUR]	1,052,000	2,105,000	864,000	1,692,000	16,470	70,588	1,982,385	5,511,425
	(B) Cost of installation [EUR]	113,000	210,000	85,000	169,000	6,900	34,500	421,500	1,047,000
	Annual maintenance cost [EUR]	47,000	100,000	51,000	153,000	3,600	18,000	31,000	99,000
Other	Major re-invest (if applicable) [EUR]	-	-	-	-	-	-	-	-
	System design life [hours]	131,400	131,400	131,400	131,400	131,400	131,400	151,500	142,100

Figure 76: Competing distributed generation technologies for industrial use cases

Economic benchmarking: The economics of stationary fuel cells

In order to evaluate the economic performance of the stationary fuel cell systems vs. the conventional technologies we have assembled and compared capital costs, maintenance costs and net energy costs. Since all use cases are primarily power driven, all technologies must cover the power requirements of each particular use case. Heat shortages or surpluses provided by the individual technologies are

calculated according to the particular load profile. Figure 77 describes the calculation methodology for the gas engine in the brewery use case.

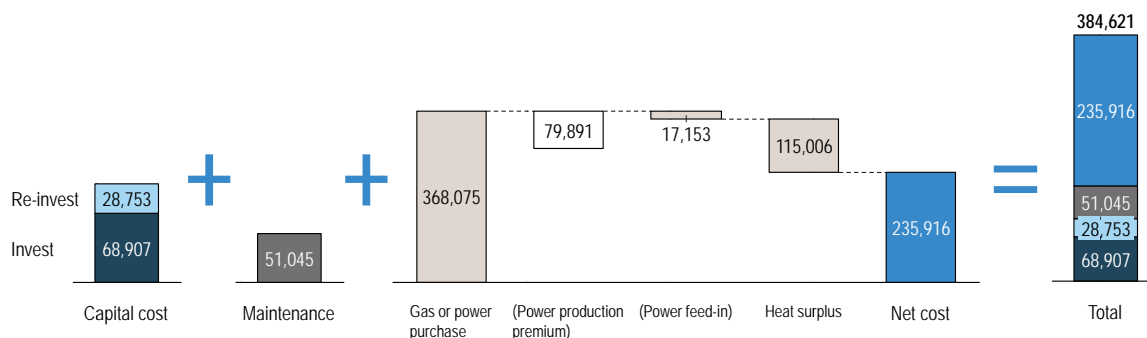


Figure 77: Exemplary calculation of total costs of ownership [EUR]¹¹²

Capital costs are calculated as an annuity over the entire lifetime of the considered system. The annuity considers re-investments necessary (i.e. stack replacements, exchanges of systems, etc.). It is driven by the cost of capital considered (i.e. 6%) and lifetime of the system. **Maintenance costs** are considered as a fixed annual amount per technology. **Net energy costs** consider fuel costs (i.e. gas or power purchase), power feed-in and heat surpluses exceeding the output of the fuel cell which can be used in each use case. Additional regulatory stimuli such as power production premium are not included in the calculation.

Data centre

The consolidated results of the data centre use case are displayed in Figure 79. Figure 78 gives an overview of the total annual energy cost today and when the first important cost-down milestone is reached (5 MW_{el} installed capacity per company).

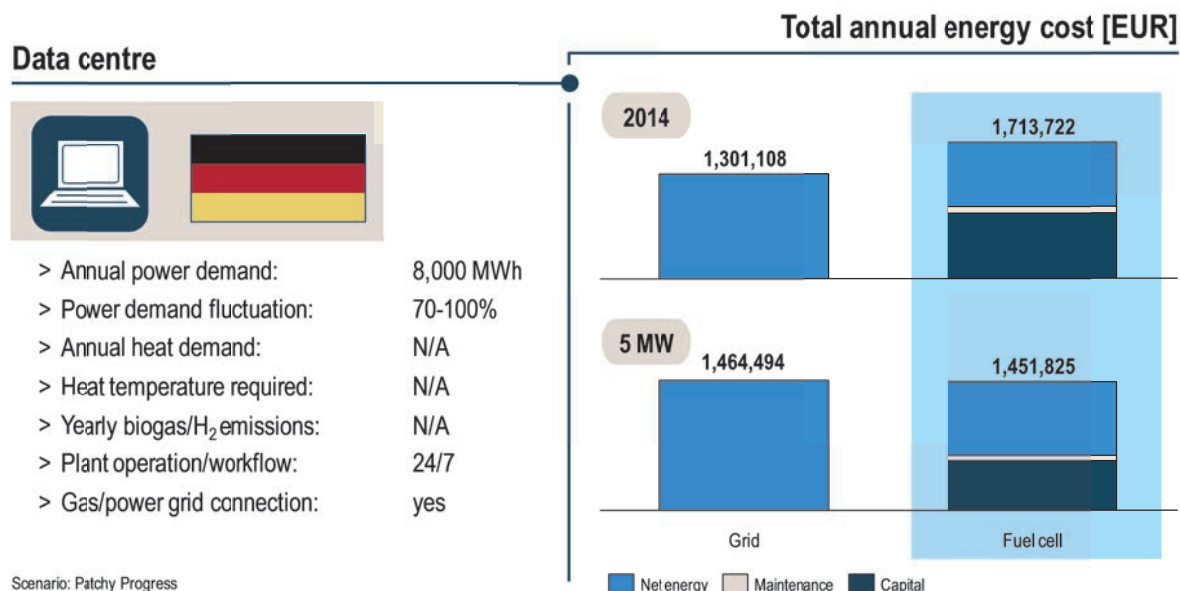


Figure 78: Economic benchmarking for data centres¹¹³

¹¹² The calculation considers the brewery use case under German market conditions in 2014 and the Patchy Progress scenario

Figure 79 displays the ratio of fuel cell total energy cost vs. competing technologies. The benchmarking results indicate that the stationary fuel cell system cannot compete against the grid in any of the focus markets. However, as outlined in Figure 78, the fuel cell may become competitive against the grid once the first 5 MW_{el} of installed capacities are reached (under Patchy Progress prices). Once the 50 MW_{el} production threshold is reached, the fuel cell becomes preferable in all focus markets but Poland.

Technology			Grid	
Country	Cost item	Unit	As is	50 MW _{el}
Germany	Total energy costs	Multiplier	1.3x	0.9x
UK	Total energy costs	Multiplier	1.4x	1.0x
Italy	Total energy costs	Multiplier	1.1x	0.8x
Poland	Total energy costs	Multiplier	2.0x	1.3x

Calculation from Patchy Progress scenario

Figure 79: Economic benchmarking results for data centres in terms of multiples¹¹⁴

Pharmaceutical production facility

The consolidated results of the pharmaceutical production facility use case are displayed in Figure 81. Figure 80 gives an overview of the total annual energy cost today and subsequent to the first important cost-down milestone achievements (5 MW_{el} installed capacity per company).

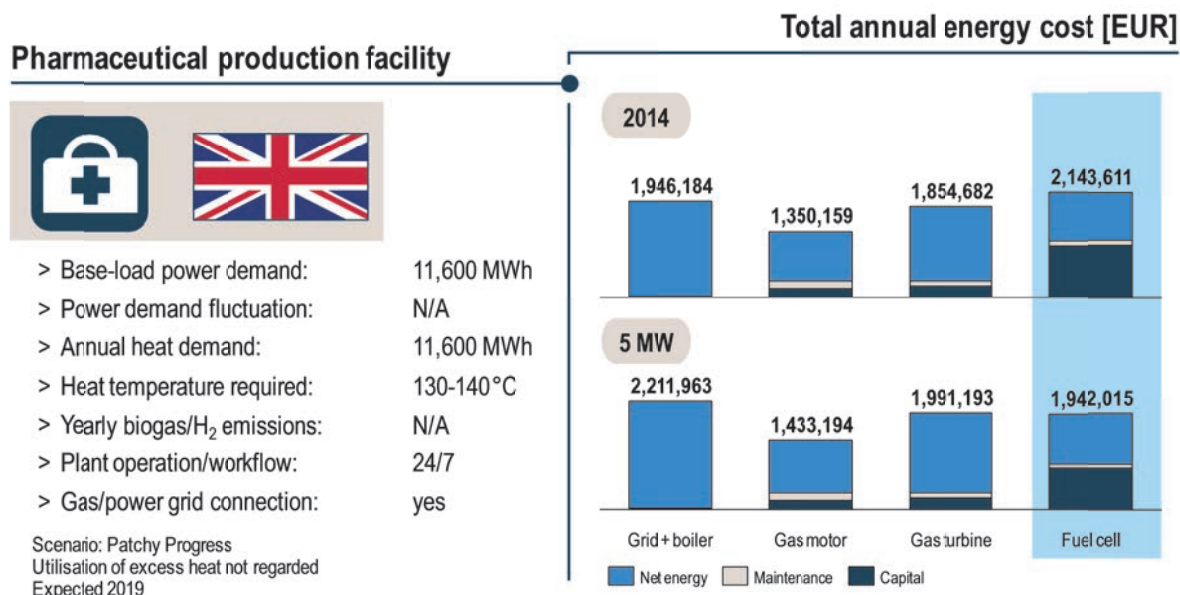


Figure 80: Economic benchmarking for pharmaceutical production facilities¹¹⁵

¹¹³ Greater upside potential is realistic if heat could be utilised and monetised, MW_{el} installed capacity expected by 2018

¹¹⁴ For cumulative production of 50 MW_{el} per company, we anticipate the year 2020 for consideration of energy prices in the Patchy Progress scenario

Figure 81 displays the ratio of fuel cell total energy cost and competing technologies. The benchmarking results indicate that the stationary fuel cell system cannot compete against the gas engine and gas turbine in any of the focus markets. However, as outlined in Figure 80, the fuel cell may significantly improve its performance once the first 5 MW_{el} of installed capacities are reached (given the prices assumed in the Patchy Progress scenario).

Technology			Grid + boiler		Gas combustion engine		Gas turbine	
Country	Cost item	Unit	As is	5 MW _{el}	As is	5 MW _{el}	As is	5 MW _{el}
Germany	Total energy costs	Multiplier	1.0x	0.8x	1.5x	1.3x	1.1x	0.9x
UK	Total energy costs	Multiplier	1.1x	0.9x	1.6x	1.4x	1.2x	1.0x
Italy	Total energy costs	Multiplier	0.9x	0.7x	1.6x	1.3x	1.1x	0.9x
Poland	Total energy costs	Multiplier	1.4x	1.1x	1.6x	1.4x	1.2x	1.0x

Figure 81: Economic benchmarking results for pharmaceutical production facilities in terms of multiples¹¹⁶

Chemical production facility

The consolidated results of the chemical production facility use case are displayed in Figure 83. Figure 82 gives an overview of the total annual energy cost today and when the first important cost-down milestone is reached (5 MW_{el} installed capacity per company).

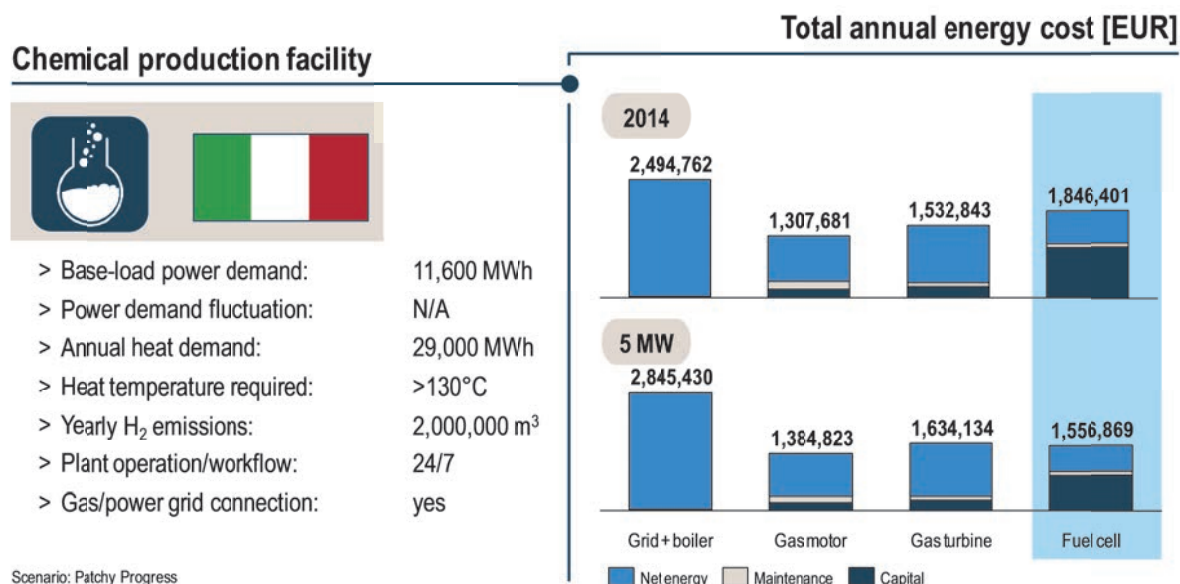


Figure 82: Economic benchmarking for chemical production facilities¹¹⁷

¹¹⁵ The utilisation of the excess heat is disregarded in the calculation. 5 MW_{el} are expected to be installed by 2017

¹¹⁶ For cumulative production of 5 MW_{el} per company, we anticipate the year 2020 for considering of energy prices in the Patchy Progress scenario

Figure 83 displays the ratio of the fuel cell total energy cost and competing technologies as is and with capital cost at 50 MWe_l cumulative production volume per company. The benchmarking results indicate that the stationary fuel cell system cannot compete against the gas engine and gas turbine in any of the focus markets. However, as outlined in Figure 82, the fuel cell may significantly improve its performance once the first 5 MWe_l of installed capacity are reached (given the prices assumed in the Patchy Progress scenario). The stationary fuel cell system is even projected to come close to the gas combustion engine by the time the 50 MWe_l milestone is reached, with a mere 10% cost difference in the Patchy Progress scenario.

Technology			Grid + boiler		Gas combustion engine		Gas turbine	
Country	Cost item	Unit	As is	50 MWe _l	As is	50 MWe _l	As is	50 MWe _l
Germany	Total energy costs	Multiplier	0.9x	0.7x	1.4x	1.2x	1.2x	1.0x
UK	Total energy costs	Multiplier	0.9x	0.6x	1.4x	1.1x	1.2x	0.9x
Italy	Total energy costs	Multiplier	0.7x	0.5x	1.4x	1.1x	1.2x	0.9x
Poland	Total energy costs	Multiplier	1.3x	0.9x	1.6x	1.3x	1.4x	1.1x

Calculation from Patchy Progress scenario

Figure 83: Economic benchmarking results in chemical production facilities in terms of multiples¹¹⁸

Brewery

The consolidated results of the brewery use case are displayed in Figure 85. Figure 84 gives an overview of the total annual energy cost today and when the first important cost-down milestone is reached (5 MWe_l installed capacity per company).

¹¹⁷ 5 MWe_l of capacity are expected to be installed by 2019

¹¹⁸ For cumulative production of 50 MWe_l per company, we anticipate the year 2020 for considering of energy prices in the Patchy Progress scenario

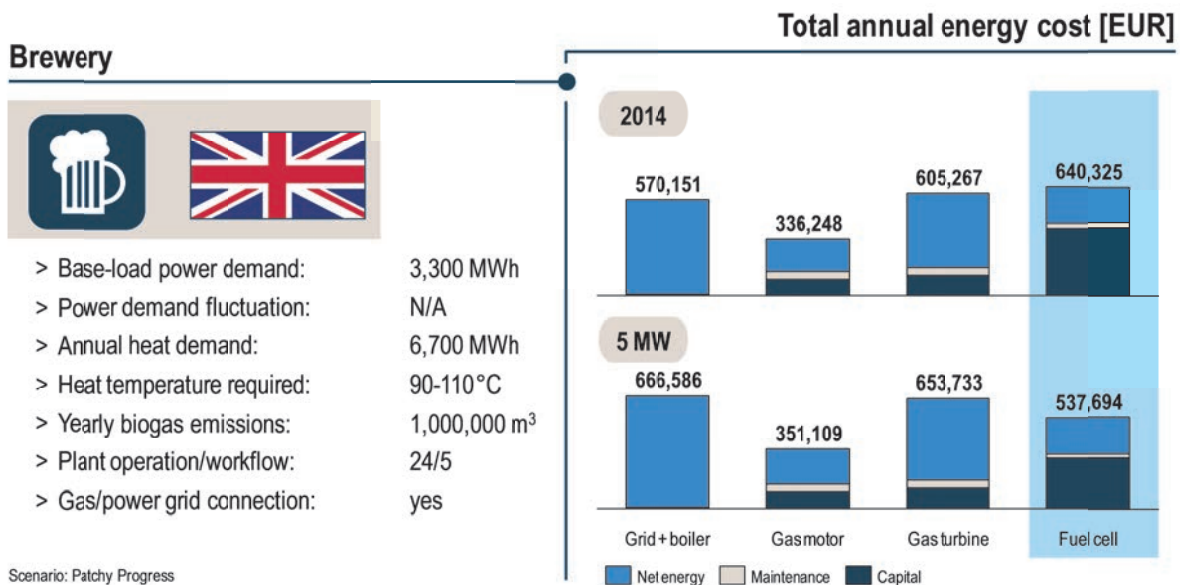


Figure 84: Economic benchmarking for breweries¹¹⁹

Figure 85 displays the ratio of fuel cell total energy cost and competing technologies as is and with capital cost at 5 MW_{el} cumulative production volume per company. The benchmarking results indicate that the stationary fuel cell system cannot compete on economic terms against the gas engine and gas turbine in any of the focus markets at present. However, as outlined in Figure 84, the fuel cell may significantly improve its performance once the first 5 MW_{el} of installed capacity are reached (given the prices assumed in the Patchy Progress scenario). The benchmarking further demonstrates that, even in the long run, the gas combustion engine appears to be the more cost-effective technology.

Technology			Grid + boiler		Gas combustion engine		Gas turbine	
Country	Cost item	Unit	As is	5 MW _{el}	As is	5 MW _{el}	As is	5 MW _{el}
Germany	Total energy costs	Multiplier	1.0x	0.8x	1.8x	1.7x	1.0x	0.9x
UK	Total energy costs	Multiplier	1.1x	0.9x	1.9x	1.7x	1.1x	0.9x
Italy	Total energy costs	Multiplier	0.9x	0.7x	1.9x	1.7x	1.0x	0.9x
Poland	Total energy costs	Multiplier	1.5x	1.2x	1.9x	1.8x	1.1x	1.0x

Figure 85: Economic benchmarking results for breweries in terms of multiples¹²⁰

Wastewater treatment facility

The consolidated results of the wastewater treatment facility use case are displayed in Figure 87. Figure 86 gives an overview of the total annual energy cost today and when the first important cost-down milestone is reached (5 MW_{el} installed capacity per company).

¹¹⁹ 5 MW_{el} of capacity are expected to be installed by 2021

¹²⁰ For cumulative production of 5 MW_{el} per company, we anticipate the year 2020 for considering of energy prices in the Patchy Progress scenario

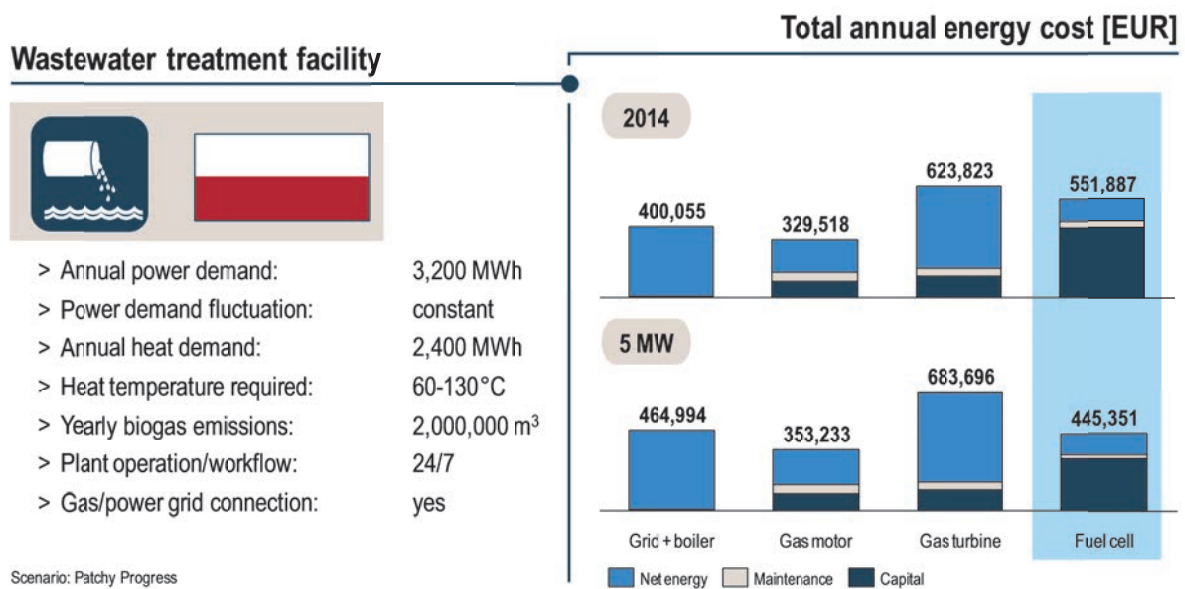


Figure 86: Economic benchmarking for wastewater treatment facilities¹²¹

Figure 87 displays the ratio of fuel cell total energy cost and competing technologies as is and with capital cost at 5 MW_{el} cumulative production volume per company. The benchmarking results indicate that the stationary fuel cell system cannot compete against the gas engine and gas turbine in any of the focus markets. However, as outlined in Figure 86, the fuel cell may significantly improve its performance once the first 5 MW_{el} of installed capacities are reached, given the prices assumed in the Patchy Progress scenario. Furthermore, the gas combustion engine appears to be the more cost-effective technology in the long run as well.

Technology			Grid + boiler		Gas combustion engine		Gas turbine	
Country	Cost item	Unit	As is	5 MW _{el}	As is	5 MW _{el}	As is	5 MW _{el}
Germany	Total energy costs	Multiplier	0.9x	0.8x	1.5x	1.3x	0.8x	0.7x
UK	Total energy costs	Multiplier	1.1x	0.9x	1.6x	1.4x	0.8x	0.7x
Italy	Total energy costs	Multiplier	0.8x	0.7x	1.6x	1.4x	0.8x	0.7x
Poland	Total energy costs	Multiplier	1.4x	1.1x	1.7x	1.5x	0.9x	0.8x

Figure 87: Economic benchmarking for wastewater treatment facilities in terms of multiples¹²²

Environmental benchmarking: The ecological footprint of the fuel cell system

The study performs the environmental benchmarking by comparing CO₂ and NO_x emissions of competing technologies in the corresponding use cases. The environmental benchmarking exceeds the individual technology emissions performance, as it considers both emissions credits (relevant in those cases in which power is fed into the grid and the corresponding emissions are lower than the equivalent

¹²¹ CAPEX for biogas storage is not considered in the calculation. 5 MW_{el} capacity are expected to be installed by 2021

¹²² For cumulative production of 5 MW_{el} per company, we anticipate the year 2020 for considering of energy prices in the Patchy Progress scenario

national power mix emissions) and additional emissions generated to cover the entire power/heat requirements in the specific use case if the technology cannot cover the entire energy demand independently. Figure 88 illustrates the benchmarking methodology for CO₂ emissions described above for the chemical production facility use case. The same methodology is used also for the NO_x emissions calculation.

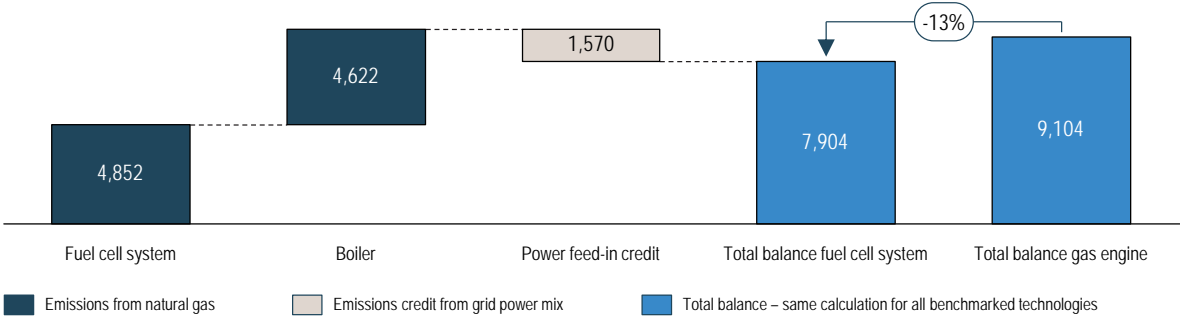


Figure 88: Calculation of total attributable annual CO₂ emissions [kg]¹²³

CO₂ emissions per technology are determined by technology efficiency and the general natural gas coefficient per kWh of fuel applied (i.e. 0.202 kg per kWh of fuel). NO_x emissions are determined by the technology efficiency and a technology specific factor.¹²⁴

The credits for power feed-in for emissions are derived from the power generation mix in the corresponding country. The same approach is used for both CO₂ and NO_x emissions.

For the use cases where a technology cannot cover the entire heat demand we assume that a condensing boiler will be used to fill the gap. As a result, the emission characteristics of the boiler are added to calculate the complete footprint for each technology.

The results of the environmental benchmarking displayed in Figure 89 indicate that the fuel cell system is superior in terms of CO₂ emissions to the grid, gas turbine and gas combustion engine in most of the use cases. In the brewery use case, however, the gas engine exceeds the total fuel cell performance due to the increased thermal efficiency of the gas boiler.

¹²³ The calculation considers the use case chemical production facilities under British market conditions in 2014 in the Patchy Progress scenario

¹²⁴ For detailed information on emission indicators, please refer to Figure 55

Country	Cost item	Use case	Unit	Grid + boiler	Gas combustion engine	Gas turbine
Germany	CO ₂ emissions	Data centre	%	69	-	-
UK	CO ₂ emissions	Data centre	%	80	-	-
Italy	CO ₂ emissions	Data centre	%	96	-	-
Poland	CO ₂ emissions	Data centre	%	40	-	-
Germany	CO ₂ emissions	Pharmaceutical	%	60	98	69
UK	CO ₂ emissions	Pharmaceutical	%	66	98	69
Italy	CO ₂ emissions	Pharmaceutical	%	76	98	69
Poland	CO ₂ emissions	Pharmaceutical	%	39	98	69
Germany	CO ₂ emissions	Chemical	%	58	84	75
UK	CO ₂ emissions	Chemical	%	64	87	78
Italy	CO ₂ emissions	Chemical	%	72	90	80
Poland	CO ₂ emissions	Chemical	%	35	70	63
Germany	CO ₂ emissions	Brewery	%	64	106	67
UK	CO ₂ emissions	Brewery	%	70	107	67
Italy	CO ₂ emissions	Brewery	%	78	107	67
Poland	CO ₂ emissions	Brewery	%	43	106	64
Germany	CO ₂ emissions	Wastewater	%	57	82	43
UK	CO ₂ emissions	Wastewater	%	63	82	43
Italy	CO ₂ emissions	Wastewater	%	73	82	43
Poland	CO ₂ emissions	Wastewater	%	36	82	43

Figure 89: Environmental benchmarking across all industrial use cases in terms of total attributable annual CO₂

When comparing the stationary fuel cell system to the gas combustion engine and gas turbine, the CO₂ advantage of the fuel cell is expected to be maintained also in the future, unless significant efficiency improvements can be achieved by the competing CHP technologies. The competitive advantage over the grid may decline over time as the decarbonisation of the European electric mix progresses and higher shares of renewable energy technologies are included.

The NO_x benchmarking results show the real strengths of the fuel cell compared to the grid and conventional CHP technologies. In the cases in which power is fed into the grid (i.e. brewery use case and chemicals use case) the stationary fuel cell system can even achieve negative NO_x emissions, due to the emissions credits granted.

Country	Cost item	Use case	Unit	Grid + boiler	Gas combustion engine	Gas turbine
Germany	NO _x emissions	Pharmaceutical	%		12	45
UK	NO _x emissions	Chemical	%		33	66
Italy	NO _x emissions	Brewery	%		33	84
Poland	NO _x emissions	Wastewater	%		0	2

Calculation from Patchy Progress scenario

Figure 90: Environmental benchmarking across all industrial use cases in terms of total attributable annual NO_x emissions shown by multiples

Other factors: Further benefits of the fuel cell system

BOX 3: Power security and back-up solutions

Power security is of prime importance in today's highly industrialised economy. The dependence on a reliable electricity infrastructure severely affects several modern-day industries. Data centres are gaining importance as society continues towards modernisation, and depends on the availability of data from the cloud for web 2.0 applications, the financial services industry, or to store essential business analytics. Beyond the internet, increasingly automated production processes could be interrupted causing unnecessary delays. Furthermore, the service sector is highly dependent on a reliable electricity supply to deliver.

Some countries in Europe, such as Portugal or Poland, are subject to interruptions more frequently and extensively than others. Particularly Germany and Denmark can rely on a considerably stable power supply. Figure 91 gives an overview of the system average interruption duration index (SAIDI), in terms of minutes of power interruptions per year, over all customers served. It becomes apparent that in comparison with America, Europe faces fewer challenges in terms of reliability.

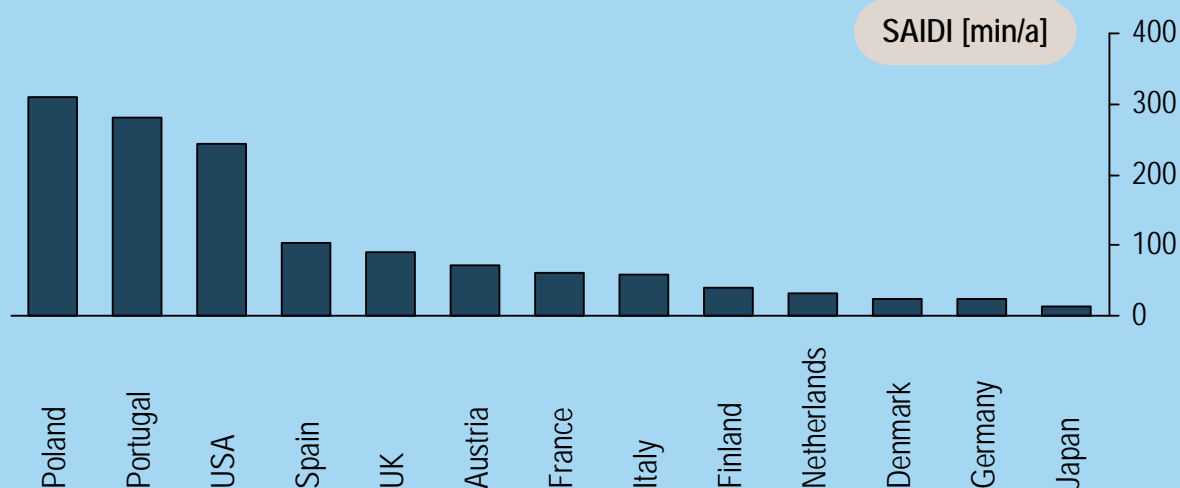


Figure 91: Reliability of grid power supply across different industrialised countries

In spite of the overall distinguished performance of European TSOs in securing electricity availability, industrial and commercial players may choose to use the grid as a back-up solution and employ the fuel cell technology to ensure power self-sufficiency. In terms of reliability, this decision is comprehensible

and sound given the superior performance of the gas grid over even leading power grids. This is made transparent in Figure 92.

A conventional alternative to gas-based decentralised power production is investing in a conventional diesel generator as a back-up solution. By switching to a gas-based solution, the grid provides back-up electricity and the 300 EUR per kW_{el} the investment in the generator would demand could be saved. In industries highly dependent on a reliable power supply, the switch to a gas-based CHP system such as the fuel cell has clear benefits in terms of reliability. Furthermore, there are clear environmental benefits of CHP and the fuel cell in particular. Therefore, as a means of independence from the grid, fuel cells clearly represent a viable and attractive solution.

In the context of power security, stationary fuel cells have moreover begun to target back-up solutions for critical industries as an important market. In North America, system developers have already started to deliver solutions for industries such as ICT, financial services and logistics. The market for back-up electricity is particularly attractive in countries like the U.S. where grid power supply is frequently interrupted and may stay interrupted for extended periods of time. In many regions across the U.S. and Canada, this is due to the structural vulnerability of power transmission and distribution networks, e.g. to natural hazards such as heavy storms.

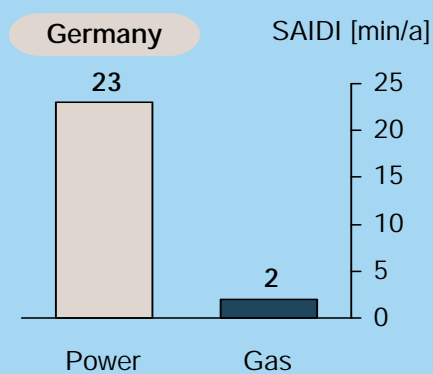


Figure 92: German power and gas network reliability

Opportunity for steam production: Larger fuel cell CHPs operating at very high temperatures (e.g. MCFCs at 700-800°C) enable the allocation of steam to industrial processes that require water at very high temperatures, making fuel cells superior to conventional, lower temperature CHP technologies like engines.

Sensitivities: External factors driving the technology benchmarking

Currently, the stationary fuel cell system is clearly the most expensive technology in terms of CAPEX. In the industrial applications segment the fuel cell is expected to decrease system costs significantly, eventually reaching 180% of the initial investment cost of the gas combustion engine. The total costs of ownership will decrease in accordance with the projected cost reductions. CAPEX reductions are expected, due to economies of scale, to occur in accordance with increasing production volumes. The corresponding values are used for the TCO calculation. For the competing technologies, constant prices are assumed due to their degree of maturity and limited competition.

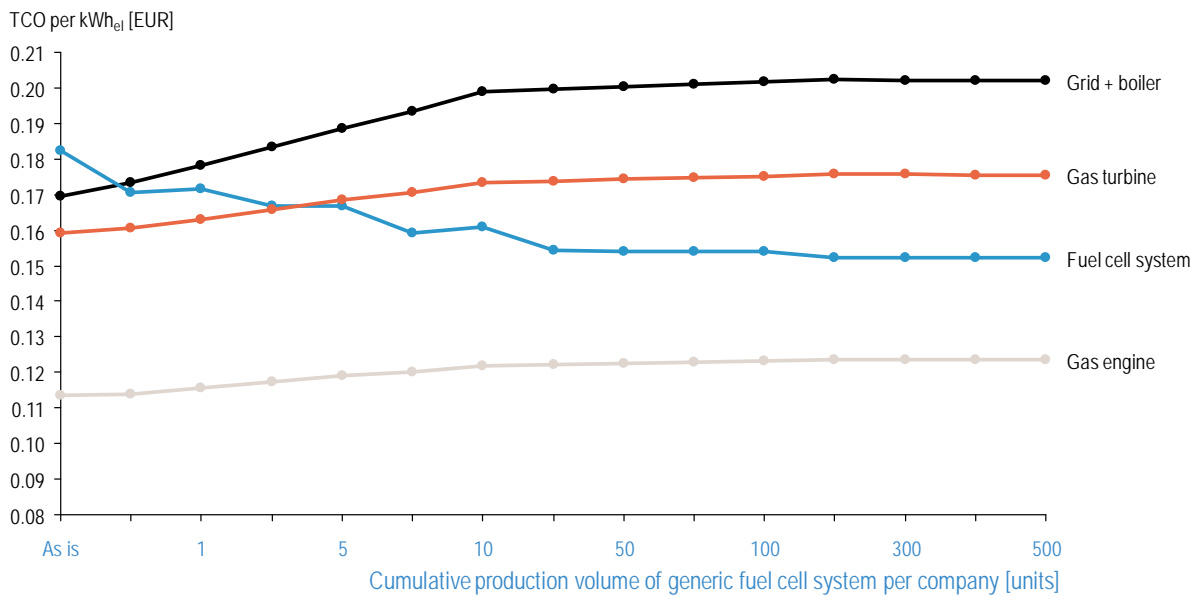


Figure 93: Total cost of ownership evolution of industrial fuel cell systems and competing technologies¹²⁵

The total cost of ownership of the stationary fuel cell system is thus expected to quickly surpass the boiler and gas turbine. However, the gas engine will maintain its leadership position in this segment. The underlying prices are based on the "Patchy Progress" scenario.

Isolating net energy costs from the analysis clearly shows the impact of the spark spread evolution in the overall performance of the stationary fuel cell system. The spark spread, as well as the gas price, thus plays a very important role for the diffusion of the fuel cell. If the spark spread changes, the relative performance changes accordingly. The impact is demonstrated in Figure 94 which is driven by the variation of the different scenarios.

¹²⁵ The calculation excludes power production premiums and other regulatory incentive schemes

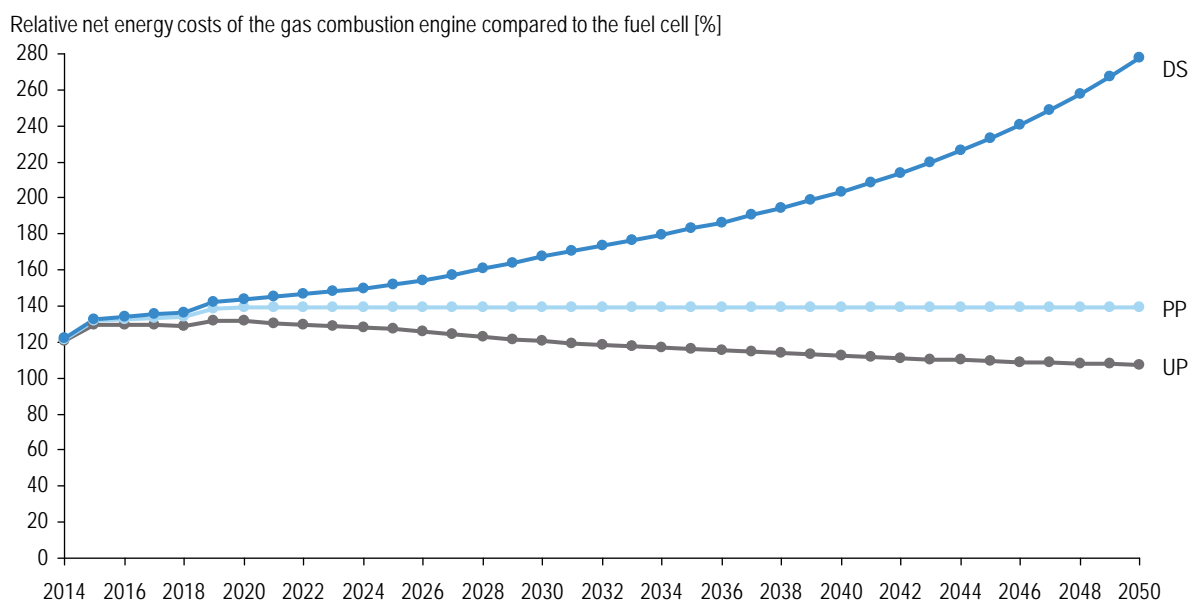


Figure 94: Relative net energy costs of the gas combustion engine compared to the stationary fuel cell system across scenarios

Figure 94 depicts the ratio of the net energy cost of the gas engine and the stationary fuel cell system. Today, the stationary fuel cell system surpasses the performance of the gas engine by approximately 20%. Given the evolution of the spark spread as well as overall improvements in efficiency (electrical and thermal, assuming the installed capacities given in Figure 93) the fuel cell system improves its performance to approximately 40% by 2020. The positive spark spread evolution has an additional impact. The "Distributed System" scenario makes the stationary fuel cell almost three times more cost-efficient, in comparison to the gas engine.

BOX 4: Grid balancing services, smart grids and virtual power plants

Several EU members have taken on the challenge of integrating variable renewables (PV and wind) into their national power mixes. In Germany, for example, total renewables contributed nearly 25% of gross power generation in 2013. Installed capacity in solar PV has increased by more than a factor of 80 over the past 10 years whilst installed capacity in wind power more than doubled. In Northern Europe, particular emphasis is laid on wind energy, which already contributes over 30% of electricity generation in Denmark, and is projected to rise to similar levels in Ireland. The integration of these sources is technically difficult, given the intermittency of power supply from wind and solar. The problems are exacerbated if these capacities are clustered geographically, and if the conventional generation lacks flexibility to follow the intermittent supply pattern of renewables. However, both PV and wind energy are indispensable for the transition to a decarbonised energy production in the European Union. Fuel cells tie in excellently with the irregular dynamics of variable renewables, given their exceptionally high efficiency and flexibility – particularly for low temperature technologies. As the deployment of wind and PV gains momentum, fuel cells can guarantee stability and reliability in national power grids.

Based on a demand signal from the utility company, stationary fuel cell applications can provide grid balancing services. Primarily, given the high electrical efficiency and very short

run-up time of low-temperature fuel cells, the technology can respond to a lack and an excess of power supply very dynamically. Electrical efficiencies between 50% and 60% stationary fuel cells require less fuel input than many conventional power plants, which often operate with inferior technological standards. In light of irregular power demand patterns on the one hand, and volatile renewable power production on the other, fuel cells can cover peak supply and peak demand periods rather smoothly. Furthermore, variable renewable power generation not met with sufficient market demand could be stored and re-generated, with seasonal capacity, using power-to-gas or hydrogen based solutions. Henceforth, an elaborate fuel cell infrastructure can play a vital role in harmonising grid imbalances.

Smart grids gain relevance quickly as the power grid becomes more difficult to manage. Renewable intermittency could be met with appropriate demand side management. Smart grids could play an important role in effectively communicating key demand indicators such as meter readings, voltage and faulty equipment to utilities, transmission system operators and regulatory authorities. This is a prime enabler of a more stable and precise power supply. Policy makers in Brussels have recognised the importance of smart grid and identified strategic Projects of Common Interest with a focus on smart grids under the TEN-E regulation. As flexible, highly efficient and comparatively clean technology, fuel cells can be a key enabler of smart grids.

Utilities can meet the stability needs of the grid by interconnecting many fuel cell applications (e.g. several dozens or hundreds of mCHPs) digitally and thereby creating a **virtual power plant**. It can rapidly respond to supply and demand fluctuations in the grid. Using smart technology, fuel cells can easily be integrated with renewables, to cover volatile heat-load conditions.

The internet of energy already receives ample attention and support from the European policy community. Some demonstrations, such as the German EDISON project, have already been conducted. To ensure an advanced and reliable load management in European electricity grids, the fuel cell technology can contribute substantially already today. In the future, advanced power-to-gas solutions could prove essential to balance demand and supply. An ample availability of fuel cells reinforces the deployment of variable renewables, and offers cutting-edge solutions to grid imbalances.

Summary of findings: Standing and perspective of the stationary fuel cell

The industrial segment is highly use-case specific and complex. Given the considerable emphasis on costs in this segment, reductions are indispensable to advance market penetration. The fuel cell system already possesses an outstanding competitive advantage with regard to net energy costs. This may even further improve, if the anticipated technical efficiency improvements are achieved. However, the positive performance in terms of net energy costs is insufficient to cover the large CAPEX gap of the stationary fuel cell compared to the conventional CHP technologies.

The stationary fuel cell system has the potential to significantly reduce CO₂ emissions across industrial use cases. The trend to decarbonise the national power mixes across Europe jeopardises the environmental performance of the stationary fuel cell system to a lower extent in the industrial segment than in the commercial and residential segment. The reason for this is that gas will continue to

be a main source for the generation of heat of the competing technologies. From an environmental perspective, the fuel cell may thus hold its preferable position longer than in the other market segments.

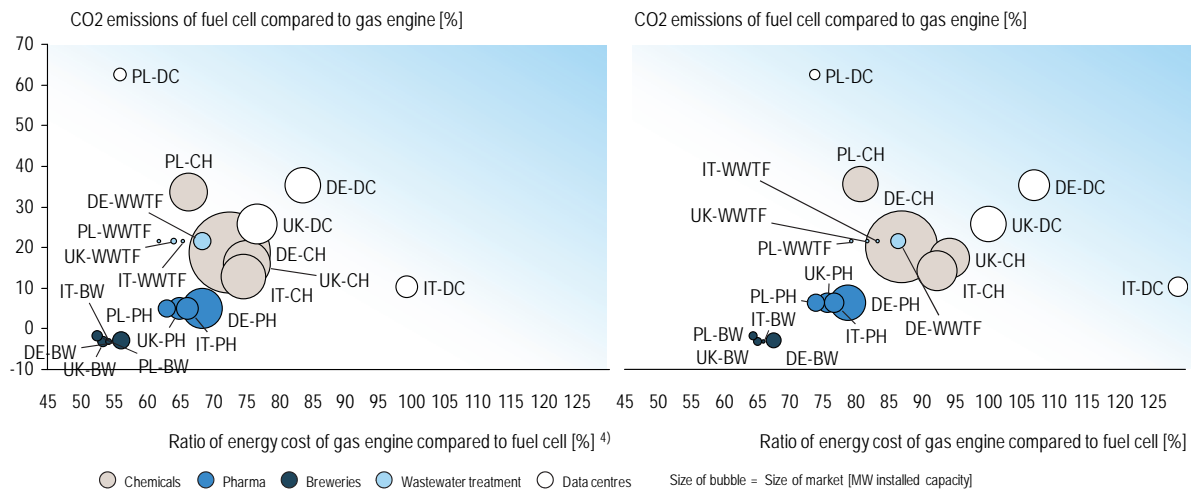


Figure 95: Match of market sizes with economic and environmental benchmarking results across all four focus markets for the industrial use cases¹²⁶

Key learnings from Chapter E

- The fuel cell has very low OPEX, attributable to savings from power production
- Significant environmental advantage over competing boiler and other conventional technologies
- Buildings with high energy demand benefit the most from CHP
- In terms of cost, the CAPEX component of the fuel cell is still too high in comparison with other technologies
- The fuel cell has higher maintenance costs than the boiler, yet lower maintenance costs than competing CHPs
- Whereas the heat pump is often preferred in buildings with a low heat demand, heat-driven integrated fuel cell CHPs are particularly suited for buildings with a high heat demand where they yield particularly high CO₂ savings and offer a better economic value proposition due to higher operating hours
- Decarbonisation of the power mix diminishes the fuel cell's environmental advantage in the long run, but the greening of the gas grid provides a remedy

¹²⁶ The size of the bubble reflects the size of the primary, addressable market. Abbreviations of use cases are used as follows: data centre (DC), chemical production facility (CH), wastewater treatment facilities (WWTF), pharmaceutical production facility (PH), brewery (BW). Data centres are benchmarked against grid supply and not gas motor. We assume 2023 prices under the "Patchy Progress" scenario for a cumulative production between 50-100 MW_{el} per manufacturer, depending on the generic fuel cell for the use case

F. Routes to market for the stationary fuel cell

The analytical work performed in this study yields several important insights on the applicability of the fuel cell technology as a heating appliance in different use cases, and the benefits this brings along. As the key learnings of Chapter E make clear, fuel cells are attractive for the residential and commercial segment in terms of OPEX, which translates into direct savings on the energy bill. In the industrial segment, the high electrical efficiency of the fuel cell and the enhanced reliability yields tangible economic benefits. Furthermore, the CO₂ reduction potential in the near term is substantial. In terms of commercialisation, it is important for the industry to re-define the prevailing value chain in general and the sales channels in particular, in order to succeed. Depending on the target group and the business model of the commercial player, the role of the fuel cell as a decentralised electricity generation technology or a heating appliance can be emphasised. The following section will give an overview of the current value chain configuration by depicting the relevant players involved in their respective fields. It will also give an outlook of how the value chain configuration could evolve over time once a higher degree of market penetration is achieved and advanced business models start to take form. Furthermore, we outline the current and potential Go-2-market strategy, and assess the roles of the relevant parties in successful commercialisation.

Residential segment: Value chain configuration and Go-2-market strategy

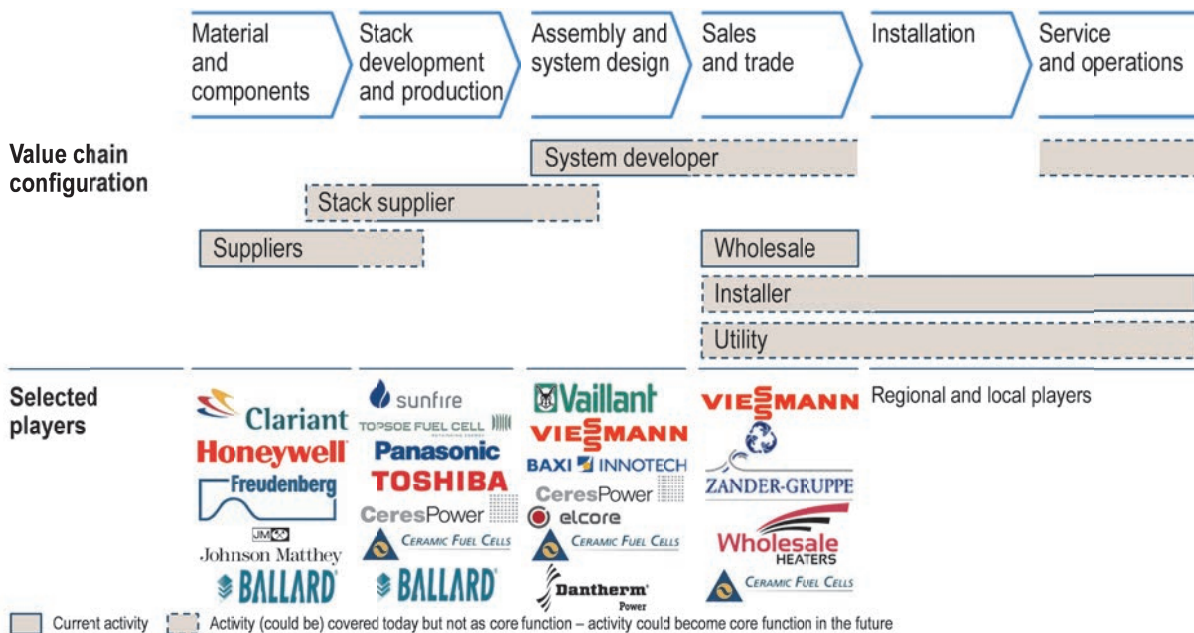


Figure 96: Value chain of stationary fuel cells for the residential segment

The residential value chain is driven by system developers and installers. Currently, assembly and system design are performed by system developers, attempting to develop easily manageable and marketable products for private households. The marketing is currently being done through wholesalers associated with the assembly company. The installation itself is performed by installers, who are characterised by a very strong local presence and close ties with the customer base. The assembly companies source fuel cell stacks and other materials from independent stack suppliers and other suppliers of components and materials. Several opportunities for an improved strategic positioning arise from this setting.

Firstly, there is good potential for a consolidation of upstream activities to generate synergetic potential and economies of scope. Therefore, it is projected that stack suppliers will expand their activities into additional supplier areas of expertise, as well as assembly design. By integrating these activities several improvements in competitiveness can be achieved. Thereby cost reductions can be achieved through synergies and the risk associated with a comparatively small European supplier base can be reduced. As the market grows and stabilises, suppliers introduce genuine process innovations for increasingly standardised products. This may also lead independent, possibly foreign, suppliers to get involved in the production of stacks. Companies currently supplying materials and components may also choose to include stacks in their product portfolio.

Furthermore, downstream players are projected to expand their activities into currently untouched spheres. Demanding customers will require sophisticated solutions including advanced warranty and regular service. Hence it is not unlikely that assembly producers could abandon the prevailing three tier distribution system in favour of direct marketing. This may make the role of wholesalers obsolete. Installers, highly established in local markets and enjoying excellent access to the customer base, could handle the one-time installation, whereas company specific service teams could handle maintenance, stack replacement and other services required. A current hurdle to the practicability of this approach is the lack of experienced CHP experts amongst the installer community. A sceptical approach to innovation and a narrow focus on conventional heating solutions may entail high margins on the installer side if risks are not shared appropriately. These problems can be circumvented following the institution and institutionalisation of appropriate training and coaching programmes by the industry. Furthermore, the establishment and maintenance of a continuous dialogue amongst the parties is indispensable, given the importance of sharing experiences and best practices. Moreover, given the close association with the customer base, installers may pursue the marketing of CHP technology directly, as well as cover post installation services. The same role may be assumed by external players such as utility companies. The latter may develop a strong interest in pursuing business in the decentralised energy generation segment out of strategic considerations.

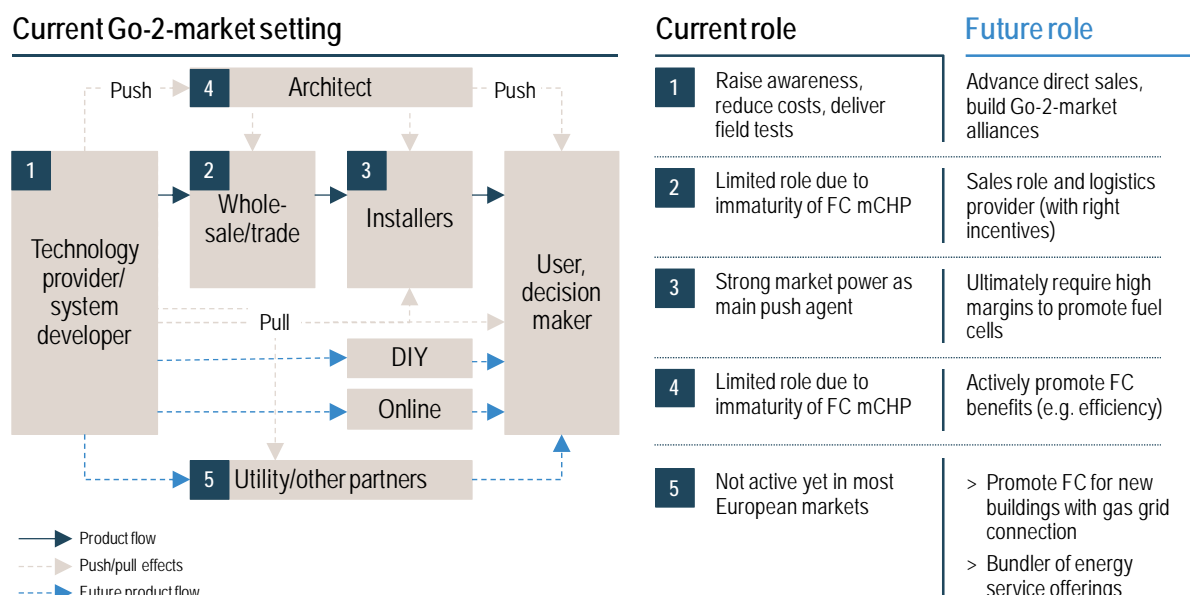


Figure 97: Go-2-market strategy for fuel cells targeting the residential segment

In order to commercialise the stationary fuel cell in the residential segment, the industry must rely on integrated and diverse marketing strategies. Currently, significant communication barriers persist between technology providers and end users (decision makers). Only in a few cases are customers

targeted directly, and the products offered may appear insufficient in their scope. Encouraging market participants to pursue a push strategy by proactively approaching their customers regularly and communicating the benefits of the fuel cell is highly important for the industry. Particularly installers are relevant in communicating the attractiveness of the stationary fuel cell as a heating appliance. Architects, currently not actively involved, could play an important role in promoting the product – particularly to the new build sector where their involvement is extensive.

Utilities who already regularly monitor a household's gas demand are in an excellent position to promote the fuel cell technology and offer concrete payment solutions if they were to adopt a business model surrounding CHP. The commercialisation of fuel cells for electricity production, rather than as a specific heating appliance, is particularly relevant to fuel cell systems. System developers could encourage this Go-2-market strategy by pursuing partnerships with utilities. A developed marketing strategy, word of mouth and political support for stationary fuel cells as heating appliances could lead to a strongly developed public awareness fuel cell benefits. Thereby, end users could be encouraged to exert a strong pull effect on the technology providers themselves.

Base-load, add-on fuel cell mCHPs targeting the electricity market: The market for distributed power generation solutions in Europe like solar PV tends to operate differently than the heating market. Customers are typically more price sensitive and products are typically sold as investment assets aiming at a specific return. Consequently, stationary fuel cells operating mainly as small power plants with little heat supply can play in a much wider field of marketing, but have less pre-established structures to work with. The contact with customers occurs via a wide range of players, such as utilities, energy consultants, installers, or other building-related players. It appears that this market field needs to be developed with more efforts than needed in the heating segment. However, if developed at some point in time the electricity market could bring higher returns.

Commercial segment: Value chain configuration and Go-2-market strategy

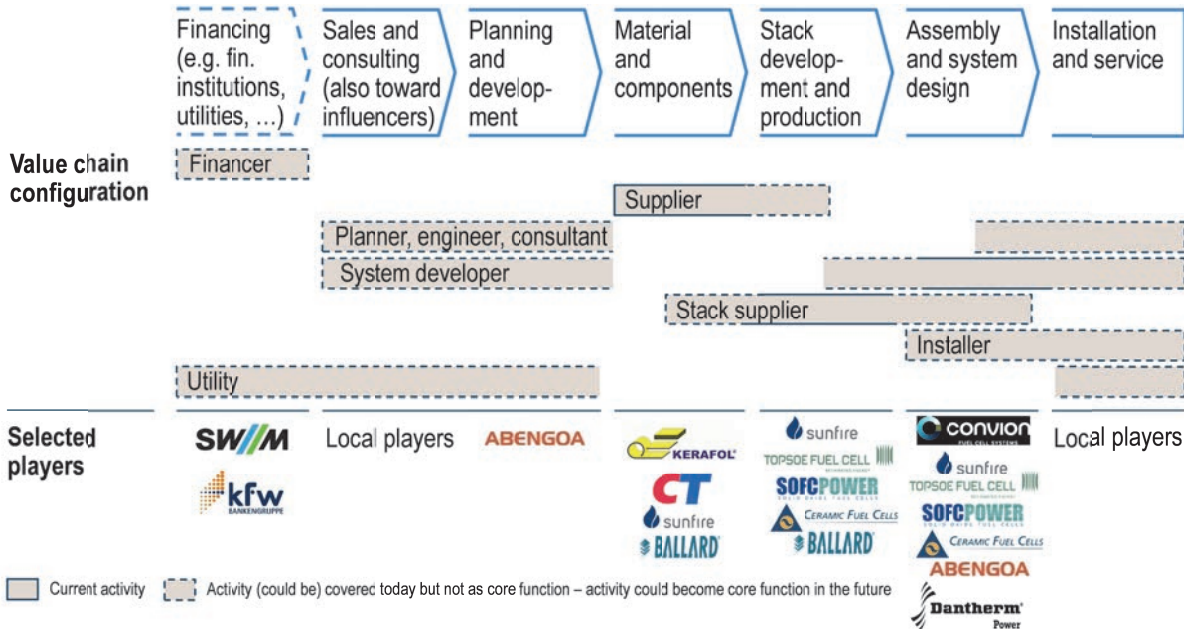


Figure 98: Value chain of stationary fuel cells for the commercial segment¹²⁷

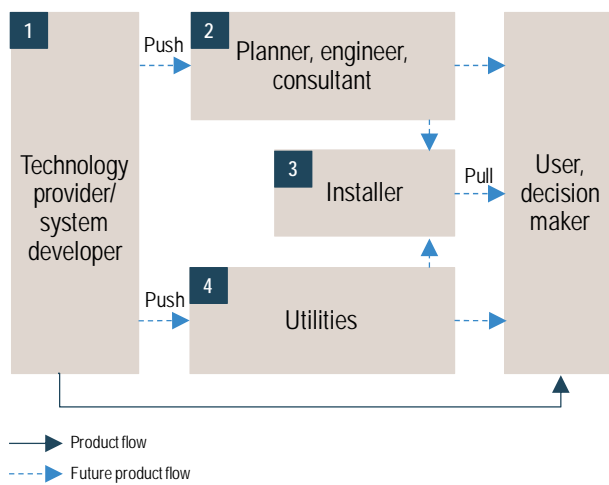
¹²⁷ Exclusive reference to systems greater than 20 kW_{el}, for 5-20 kW_{el} units please refer to the residential segment

Suppliers and system developers currently dominate the commercial value chain. The latter perform assembly and system design. Stack suppliers are usually specialists in their field, with little experience in product assembly or heating system design. Materials and components are sourced from additional suppliers. Commercial buildings may require systems to be designed with specific characteristics matching heat and power profile and the maximum load requirements. Standardised products may prove to be widely applicable in apartment buildings, yet hospitals and other major facilities demand specifically tailored solutions. These, particularly large, projects require upfront financing, however hardly any European players stand out in this area to date. Figure 98 shows how the value chain could potentially develop if more activities were covered by existing players, or if strategic alliances were formed with external players in the market.

There is great room to accommodate additional players in the upstream value chain activities. Financing is an essential step in the value chain given the commercial sector's strong sensitivity to costs. Investor confidence in stationary fuel cells is crucial to successful commercialisation, by providing B2C financing. Currently, interest is guarded. Utilities, often endowed with good access to financing, could also serve as potential financiers in the future. Direct sales and planning and consulting could be performed by planners, engineers, consultants or system developers. Whereas the latter would have to establish a local presence, engineering, planning and consulting offices are already well established players, with good access to a broad customer base in the commercial sector and very knowledgeable of the demand requirements. However, these players still have a poorly developed knowledge of the fuel cell. System developers can benefit from establishing strategic alliances with these players in the market.

In terms of downstream activities, existing players could become more integrated and seek partnerships and alliances. With regard to manufacturing and supply chain, it is highly likely that those players currently active in these areas, namely suppliers and system developers, will expand their activities into different areas of the value chain. By integrating value-add steps within the same company, the market can be stabilised by reducing the risk of supplier exits. Furthermore, price uncertainty can be circumvented by becoming active in more areas of the value chain. Installers, planners, engineers, consultants and utilities are identified as players with potentially excellent access to the customer base. At present, no player has established a strong presence in the installation and service market. In the future, it is likely that those players with a strong customer base will reinforce their capacities in this area and arrange strategic partnerships with system developers to optimise the product flow and gain access to a larger market. Particularly utilities, who can make use of the high efficiency of the fuel cell for electricity generation could benefit from this model. Moreover, system developers can establish a direct channel to the customer. This would require the establishment of locally organised installation and service units. One advantage of this is a better knowledge of the technology than installers and energy planners and utilities, who may require comprehensive training.

Go-2-market setting



Mid-term role

- 1 Raise awareness, reduce costs, deliver demonstration projects
- 2 Directly involved in decision for heating system – **key influencer**
- 3 Limited role – no direct link to technology providers
- 4 No involvement in Go-2-market

Long-term role

- Advance direct sales, build Go-2-market alliances
- B2C sales and logistics provider for standardised products
- Licensed providers of FC technology, first contact person for consumers
- Local footprint – close customer relationship

Figure 99: Go-2-market strategy for fuel cells targeting the commercial segment¹²⁸

The Go-2-market strategy for the commercial segment may require different organisational processes than the residential segment. One primary element of distinction is the role of planners, engineers and consultants in communicating the benefits, and directly marketing the fuel cell. Large buildings may require a detailed analysis of heating requirements and electricity demand patterns in order to assess the economic viability of stationary fuel cells and the technical specifications. This is in contrast to the residential segment, where the installation can be performed comparatively easily by a certified installer. Planners, engineers and consultants are key influencers in the commercial segment and may exert a strong push effect on the market, in favour of fuel cells as a heating system. Technology providers should therefore seek close collaboration with these players. Installers are expected to be subcontracted, although their role may develop in the future by becoming a first contact centre for end users. Utilities could also play an important role in the Go-2-market strategy, given their current business association with end users over the gas grid.

Utilities can provide a coherent business case with stationary fuel cells to commercial customers for electricity generation by drafting power purchase agreements. They are particularly close to the customer base given their strong regional footprint, which can inspire confidence in local business owners and large public facility managers. The high electrical efficiency of the fuel cell makes stationary fuel cells for distributed electricity generation an interesting perspective for utilities. Customers within the commercial segment, particularly sensitive to sound business cases and comprehensible contractual arrangements, may prefer to purchase both power and heat from a single entity.

¹²⁸ This setting will apply at a later stage in product development, after successful demonstration projects and field tests

Industrial segment: Value chain configuration and Go-2-market strategy

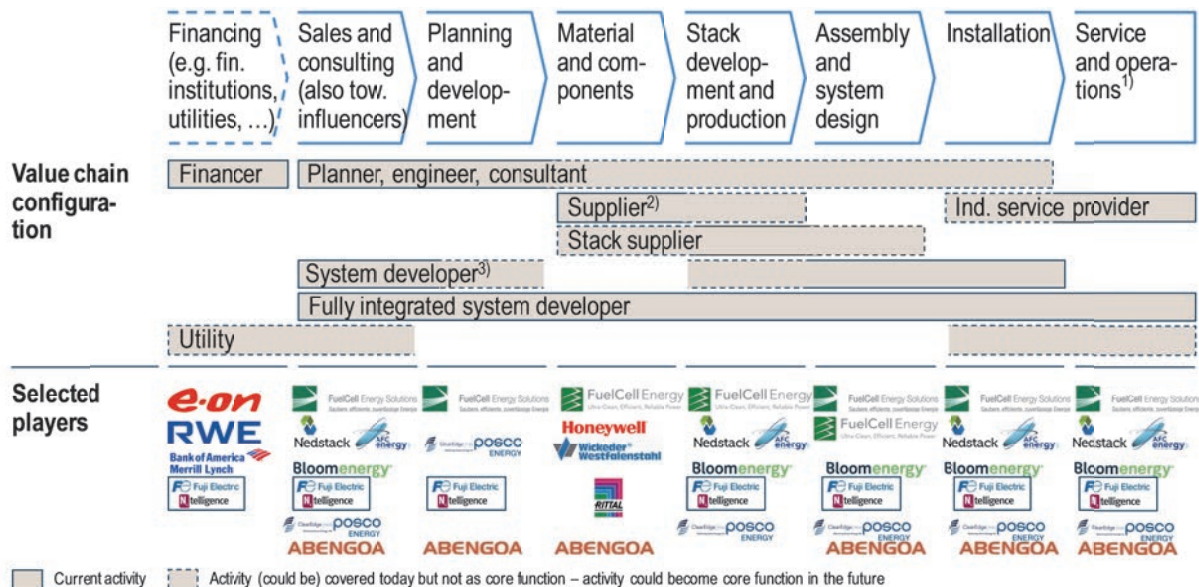


Figure 100: Value chain of stationary fuel cells for the industrial segment

Whereas the residential and commercial value chains discussed above had great room for new organisational patterns, **the configuration of the industrial value chain is projected to remain relatively static in the long run.** The financing of decentralised electricity generation projects using fuel cells is the first step, and a crucial component, of the value chain. Leases, for example, have proven to be easily implemented and well received by customers of renewable energy technology and CHP technology. Planners, engineers and consultants play an important role in the value chain configuration. Specialised offices currently cover both planning and sales. System developers in the market also have a direct sales channel, though their primary business is the assembly and installation. Specialised industrial service providers usually perform the regular servicing of the equipment. Some companies have fully integrated the value-add steps and seek a direct channel to industrial customers. Therefore, partnerships with industrial service providers are bypassed. Furthermore, whereas system developers usually source stacks and other supplies from specialised suppliers operating in the market, fully integrated developers can rely on in-house capacities.

Financing requires close attention as the first step of **the upstream value chain.** Some financiers are already in the market, however it is likely that the number of financiers will increase as the technology builds a strong reputation. A currently high perceived risk can be removed through successful and visible industrial projects. Furthermore, **utilities could enter the market in the future and offer financial solutions to industrial customers.** These institutions can also leverage the customer base given that business associations are already established for the supply of gas and power to industrial recipients. Their internal planning and energy modelling expertise could further serve as an excellent basis to expand their activities in the stationary fuel cell market. Particularly system developers are still lacking access to this expertise, which is why it is expected that they will either expand their own capacities to include planning and development, or form Go-2-market partnerships with professional planners, engineers or utilities.

Players who are active in production are expected to expand their activities. Suppliers, currently focused on material and components, could integrate a stack production of their own in order to tighten their business association with system developers. Furthermore, stack suppliers could become active in the supply of components and materials and consider building up assembly lines themselves. Synergies

in production and sourcing may reduce costs and build competitive advantages in the market place. Furthermore, these developments encourage increasing standardisation of stacks and the harmonisation of components and assembly technology. Thereby, the production of fuel cells can be continuously improved. System developers could integrate stack manufacturing within the scope of their business. The risk of unforeseen supplier market exits can thus be reduced whereby sales, operations and production planning become more easily calculable.

Downstream activities such as installation and system operation are currently performed by either fully integrated system developers or industrial service providers. Currently, only system developers perform installations. However, planners, industrial service providers and utilities are also expected to build up capacities to perform installations as the market progresses. Utilities can leverage their existing workforce and system developers can establish strategic partnerships with industrial service providers to perform services following installation.

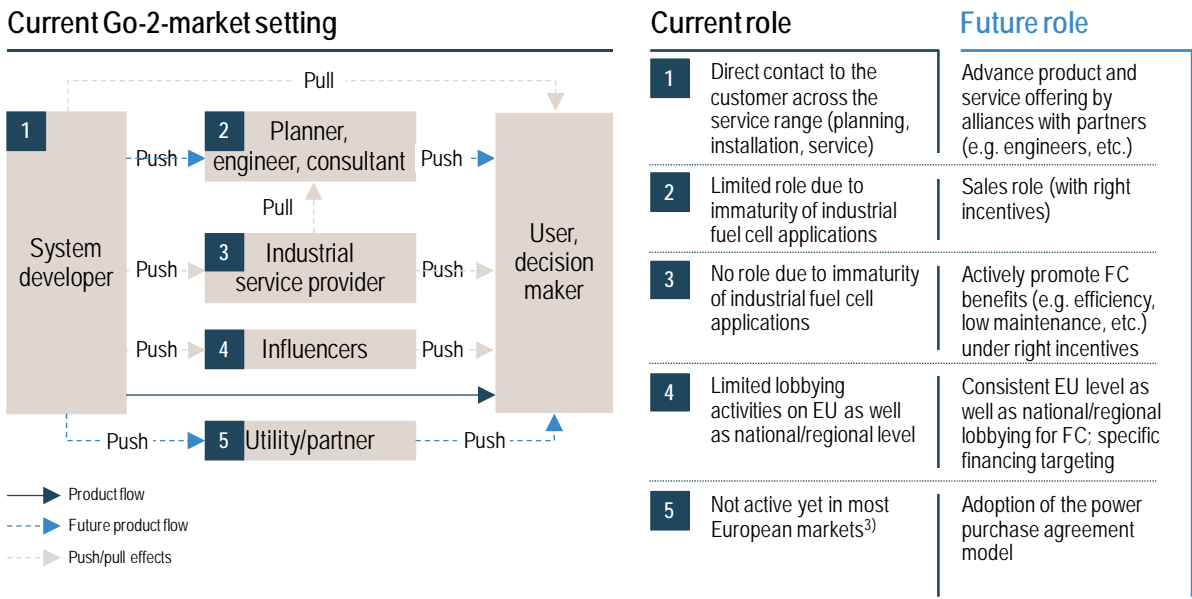


Figure 101: Go-2-market strategy for fuel cells targeting the industrial segment

The industrial Go-2-market is currently dominated by the system developer. However, this marketing channel is limited in its scope. A successful commercialisation manages to leverage the customer base by including additional players such as planners, engineers, consultants, industrial service providers and utilities in the direct sales channel.

System developers currently depend on direct contact with the customer. However their outreach is constrained given that the awareness of the technology is still limited amongst the European industry. System providers ought to push those players already active in the market to promote the stationary fuel cell technology. This can be done by seeking strategic partnerships with planners, engineers and energy consultants to include fuel cells in their product portfolio. These players can leverage the customer base considerably, given their extensive involvement in the construction sector. Furthermore, it may prove strategic and attentive to seek commercial partnerships with utility companies. On the one hand, utilities are the primary contacts for drafting power purchase agreements (PPAs) with independent industrial producers. On the other hand utilities can play an active role in developing financing models tailored to fit the customer's financial situation and power security requirements.

It is important to increase the general awareness of the stationary fuel cell amongst the industrial auto-production community. Policy, amongst other influencers, can play an important role in this respect

by embracing decentralised energy generation in the political discourse and highlighting the benefits of combined heat and power production. This political backing could translate into a great leap for the technology in terms of commercialisation.

BOX 5: Revenue models

The successful commercialisation of the fuel cell depends to a very large extent on the choice of revenue model. Total revenue will depend crucially on the scope of the offer to the customer. The study builds on the experiences and best practices of industry experts active in the residential, commercial and industrial segments to identify the most promising models for stationary fuel cells.

Possible revenue models







+	Product and service	Full service contracting	Product scope
-	Product sale	Product and warranty	
	-	+	

Transaction timeframe

Other relevant revenue models

- > ESCO model
- > Licensing

Attractiveness of revenue models

Product sale		<ul style="list-style-type: none"> > High system cost > Lack of customer service could alarm investors
Product and service		<ul style="list-style-type: none"> > Substantial operational risk for the customer as well as financial risks
Product and warranty		<ul style="list-style-type: none"> > Suboptimal usage of system on the customer's part can result in high risks for the system supplier
Full service contracting		<ul style="list-style-type: none"> > Reduced operational risk for both supplier and customer > Well received by decision makers
ESCO model		<ul style="list-style-type: none"> > Customer bypasses high initial investment > Financing of system and the associated risks is the key issue
Licensing		<ul style="list-style-type: none"> > Pooling of volumes with other suppliers > Royalty income

Level of attractiveness:  Low  High

Figure 102: Revenue models for stationary fuel cell systems

System developers are faced with a choice on how to market their stationary products to a wide array of strongly heterogeneous consumers. Industry experts are aware of the current hurdles to commercialisation,¹²⁹ and view the simple sale of the product as insufficient to gain prominence in the marketplace. We believe that the novelty of the technology may be met with initial scepticism by consumers, which is why it is crucial to inspire security and authenticity as part of the business strategy. The sale of solely the product may hence not be met with enthusiasm on the consumer side. Including regular service as part of a package with the fuel cell system somewhat alleviates this problem. However, the risk of technology defects would remain on the consumer's side. Given the novelty of the technology in the market, this strategy may prove unsatisfactory for both suppliers and consumers. If the supplier was to include a warranty alongside the product, the risk transfer from the consumer would be complete. However, the lack of a service contract could signal long response times in case of underperformance. This is particularly disquieting to, particularly residential and commercial, consumers because many heating system installers established locally are still unfamiliar with the fuel cell technology. Furthermore, and perhaps most importantly, a high initial investment is very discouraging to the consumer. Therefore, for as long as the initial payment required is very high, an alternative revenue

¹²⁹ For more information, please refer to Chapter G

models should be considered by consumers.

We agree with the experiences of industry experts who identified full service contracting as the most promising revenue model for the fuel cell industry. This package should include the upfront installation, operation, regular maintenance and a sophisticated fault clearing service, with the customer being billed monthly as opposed to upfront. This has the advantage of bridging the initial investment hurdle particularly residential and commercial customers face, and provides a sense of reliability to the consumer by yielding the responsibility for the technical equipment to the supplier.

There are some experiences in the market with this business model. Particularly EWE in Germany is worth mentioning in this respect, given their carefully drafted consumer friendly packages for residential, commercial and industrial users. Other local energy companies have also had experiences with contracting, although the experiences are largely limited to the installation of competing CHP and renewable technologies in the commercial segment.

This study has identified complex decision chains as one hurdle for the deployment of stationary fuel cells to apartment buildings. A full service contracting model can sidestep this obstacle to some extent by billing only those residents willing to accommodate a fuel cell on the premises, and installing a model suitable to the actual demand. Those residents willing to partake could be organised in associations and file the order to the contractor.

Furthermore, we identify the ESCO model as a highly promising solution for the commercialisation of the fuel cell. A prime advantage of the stationary fuel cell as a heating appliance is the lower cost of operation, owing to fuel savings. System developers could benefit from a model, where the regular customer savings consist of a large fraction of the energy savings the customer enjoys by installing the system, in return for the upfront provision of the system. This model has already gained a strong reputation in the UK and we view it as applicable to additional commercial and industrial customers in Europe.

A third alternative for system developers consists of licensing their technology to third parties in return for a royalty. The latter could provide greater numbers of units to the market. Thereby, the technology would be introduced to the market and cost reductions could be achieved, without OEMs being forced to compete in a very difficult market environment. In terms of market dynamics, however, the producing OEM may have a first mover advantage.

Key learnings from Chapter F

- System developers should form alliances with established players upstream and downstream in their value chains
- Utilities could play an important role in commercialising stationary fuel cells by leveraging the customer base and developing revenue models
- Greater communication by policy makers is required
- Suppliers could integrate more value-add steps
- Securing financial support is highly important
- Full service contracting and the ESCO model are particularly viable revenue models

G. Potential barriers to commercialisation

The goal of commercialising the fuel cell and establishing it permanently in the energy technology pool of the future hinges on the successful evasion of the currently perceivable barriers. The barriers identified and elaborated upon in this section form the basis for the recommendations in the subsequent chapter.

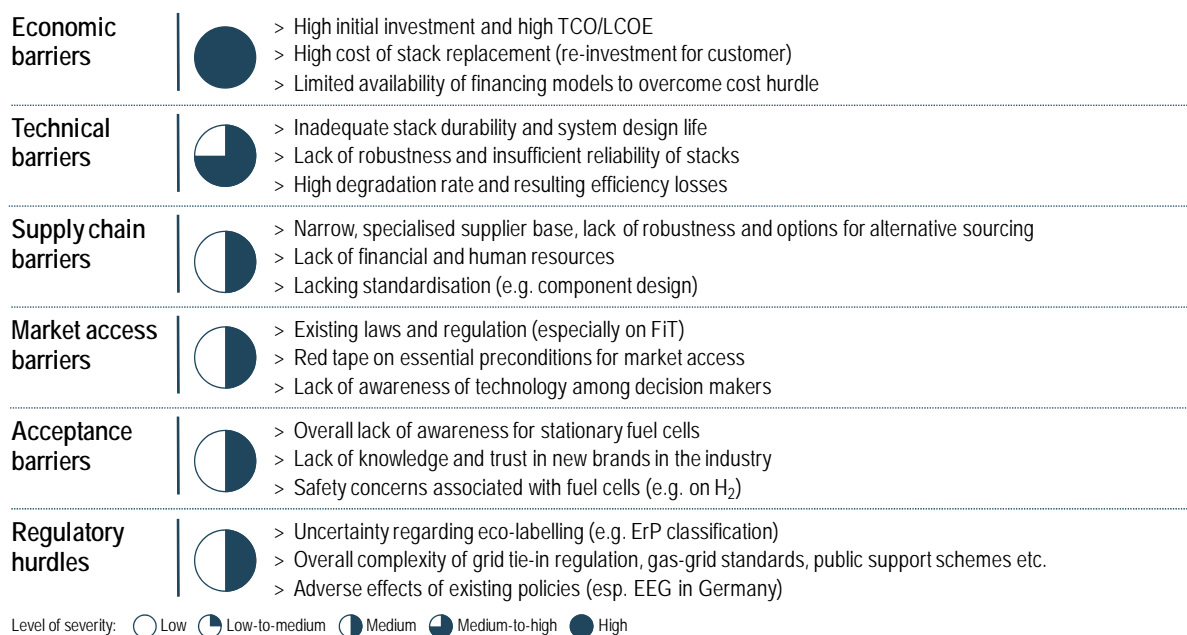


Figure 103: Major barriers to commercialisation for stationary fuel cells and their severity

High initial investment costs are still the primary economic barrier to extensive commercialisation of the fuel cell. Particularly industrial and commercial consumers are highly price sensitive and may be discouraged from investing given a high initial cost and an uncertain payback period. Furthermore, the additional costs that must be incurred due to the necessity of stack replacements over the lifetime of the fuel cell may preclude the decision for the fuel cell. This is also true for the residential segment, given that the price tag of the fuel cell module has a high impact on the investment decision. Appropriate business models are one remedy to bridge this hurdle, however price tag reductions are indispensable.¹³⁰

Given their higher overall value propositions as innovative CHP solutions, fuel cell CHPs will likely remain more expensive in mere CAPEX-terms than conventional heating technologies like condensing boilers. To overcome this hurdle especially in price-sensitive markets and segments, it is imperative to enable non-cash-sale transactions for distributed generation technologies. Consequently, any regulatory barriers to innovative financing models (e.g. leasing, contracting) should be removed to allow fuel cells to commercialise.

There is still overwhelming potential to improve the production process itself. Batch sizes are small leading to prolonged set-up times and too many heating cycles. Process steps such as cleaning, spraying and firing could be improved further in order to reduce scrap rates and optimise the cycle times

¹³⁰ Please refer to Chapter E for more information

of individual units. Some companies have succeeded in semi-automating the stacking process, however some companies still need to make this step. Furthermore, inspection is highly manually intensive, leading to unnecessary time consumption in the production process and high labour costs per unit. Improved production cycles and production organisation in both stack manufacturing and end-product assembly can lead to a higher degree of equipment utilisation and thereby drive down costs.

The fuel cell technology itself still has some room for improvement. Industry experts are confident that technological complexities will be resolved shortly and project further efficiency and stack durability increases in the near future. Currently, however, stack durability and system lifetime are not fully developed. As the in-house testing and applications in the market increase, the average degradation rate is expected to decrease, leading to higher efficiencies. The number of stack replacements required is highly visible to the customer and may hence be interpreted as a quality signal. Experience in the fuel cell market has shown that improvements in terms of average stack degradation rates and lifetime improvements can be achieved within very short periods of time given sufficient company in-house research and in-field testing in the course of demonstration projects.

The European fuel cell industry still relies on a comparatively narrow supplier base, with considerable risk of unexpected supplier exits. Upstream players are often highly specialised with insufficient access to reliable financing and appropriate human resources. Furthermore, those companies specialised in assembly and system design encounter some difficulties in sourcing stacks due to insufficient standardisation of the product. The lack of competitive sourcing therefore represents a considerable barrier to the fuel cell industry at present.

This study identifies a series of market barriers the industry should address in the course of commercialisation. Particularly the residential segment manifests a noteworthy path dependency in the customer's decision making process. This implies a dominant position of conventional heating systems, which cannot be easily discontinued. Somewhat aggravating to this situation is the apparent lack of awareness on the demand side of the benefits of the fuel cell. A clear policy commitment which incorporates the strengthening of feed-in tariff schemes may prove helpful in this respect. Furthermore, market access for the stationary fuel cell is more challenging in areas without a gas grid connection. Although the gas grid is extensive in some countries, such as the UK, some countries are witnessing declining investment in their gas infrastructure – e.g. because residential developments with very energy efficient new buildings speak against a connection to the gas grid.

Another barrier to the commercialisation of the fuel cell is the acceptance amongst consumers of this novel technology. As mentioned above, this is partly due to the lack of awareness of the fuel cell technology in general and the specific benefits in particular. Conventional heating technologies are well known by consumers in terms of operation. Some consumers may have safety concerns for their home, and decide to remain with a more established technology. Others may distrust some of the new brands that may appear in the market place. We expect the acceptance barrier to be more significant in apartment buildings than in 1-2 party residences, given that the decision processes are more complex and often require the consent of all parties involved. Suitable revenue models and a carefully drafted business model may help overcome this hurdle.

Regulatory hurdles make up another potentially major barrier to commercialisation. The environmental performance of energy related products (ErP) is made transparent to the consumer through the corresponding energy labels, mandatory by 2015. There is some uncertainty surrounding the classification the gas-based stationary fuel cells will receive. Furthermore, the environmental performance of the fuel cell becomes less significant as Europe decarbonises. Therefore, it remains uncertain how long the stationary fuel cell will be considered an environmentally beneficial. Additional regulatory complexities evolve around the issue of to what extent fuel cells can be fully integrated as

decentralised power producing stations. There are varying regional and national approaches to this topic, which translate into heterogeneous technology requirements that need to be met in order to be eligible for public support schemes. Consequently, the marketing of truly standardised products is hindered.



Figure 104: Minor barriers to commercialisation for stationary fuel cells and their severity

In several European markets, stationary fuel cells will have to comply with several key **permitting procedures** in order to be eligible for public support and extensive commercialisation. This involves not only general safety requirements, but also legislation surrounding voltage regulation and the usage of indoor gas appliances. Furthermore, installations have to be performed by trained and certified staff. Their lack or insufficient availability could represent a potential barrier in the early stages of deployment.

Competing companies in the European heat and power market pursue strategies of their own. Europe has embarked upon an ambitious road to decarbonising the energy supply and making consumption as energy efficient as possible. Different approaches to this are still underway, some of which antagonise the concept of decentralised energy generation. There is a possibility that the comprehensive deployment of stationary fuel cells for electricity generation may be met with opposition from large utility companies. Furthermore, established players in the heating market producing conventional heating technologies may also advertise the presumed superiority of their technology.

Intra-corporate competition for the predominant heating solution does not seem to represent a major barrier to commercialisation in the European heating market.

Other barriers include a presumed lack of sufficiently trained staff in some European markets for the extensive deployment of the fuel cell technology, in the light of the novelty of the technology, and weak communication of the successes to the general public. This challenge may be exacerbated by conflicting positions and visions for the future of European energy supply that fail to embrace the stationary fuel cell as a means of achieving energy policy objectives. However, these barriers are considered to be minor and hardly resolute.

Key learnings from Chapter G

- High costs are the greatest obstacle to commercialisation
- Technical challenges persist, particularly regarding stack durability and reliability
- Lacking standardisation creates challenges in the supply chain
- Lack of awareness amongst the general public of stationary fuel cells
- Policy commitment to the fuel cell is insufficient

H. EXCURSUS: General policy framework

This chapter gives a brief overview of support schemes in the EU and other relevant regions for stationary fuel cells and CHP systems, in order to highlight the varying financial and political commitment to the technology.

The global policy debate on fuel cells takes place in the greater context of the transition into new energy systems that are more efficient and more sustainable. Alternative energies have become increasingly important in recent years, attracting more focus from policy makers. As renewable energy sources such as wind and solar are intermittent in nature, policy makers are focusing more and more on developing alternative and continuously available methods for heat and power generation. In this context, fuel cells have captured a rising share of interest because of their potential of being a reliable, highly efficient, and low-emission source of energy. Policy makers and technology providers have begun exploring the benefits of stationary fuel cells and are increasingly pushing towards their commercialisation. Support schemes for fuel cells are ongoing, although mostly outside of Europe until recently. The most conducive policy frameworks for stationary fuel cells exist in Japan, South Korea and the USA. In these markets, support schemes have led to substantial progress in commercialisation, significant increases in production volumes and consequently considerable cost reductions of stationary fuel cell systems. Specifically, support schemes in Asia target the large-scale diffusion of residential fuel cell CHP system, whereas the USA's support schemes focus mainly on the deployment of industrial systems. Fuel cell systems for commercial buildings (at medium power range) were, to a great extent, not within the scope of existing support schemes. Whilst Europe still has a lot of catching up to do regarding policy support for fuel cell diffusion, several EU-wide and country specific support schemes for fuel cell technology already exist and are expected to amplify both in scope and number in the coming years.

By presenting basic facts and figures for selected support schemes, as well as objectives, measures, (intermediate) results, and key learnings, we profile different alternatives for public policy intervention to advance the commercialisation of stationary fuel cells. The following tables help clarify the typologies we use to categorise support schemes.

Instrument types

Grants	Money given to organisational entities by the government to benefit the development of alternative energies, e.g. through research and development
Subsidies	Money paid to users/consumers by the government to incentivise the installation of emission reducing technologies
Tariffs	Long-term contracts with (private) alternative energy producers to promote use of cleaner energy production methods
Tax credits	Reduction of federal or state income taxes due to capital investments in alternative energy projects that are tax deductible
Trading	Construction of markets to trade emission certificates between industrial consumers of energy; incentivises companies to watch their footprint without inducing extensive governmental expenditure

Programme types

Push	Programmes that sanction entities (e.g. by imposing fines or other penalties) for non-conformity with (newly introduced) laws and regulations
Pull	Programmes that incentivise proactive change towards alternative energy production
Hybrid	A mixture of push and pull methods

Europe: Overview of support schemes

Policy support for fuel cell technology in Europe has been conservative compared to other countries. However, the EU's interest in and political commitment to fuel cells has gained momentum in the recent past. EU-instigated support of the technology currently comprises grants for research and development as well as various demonstration projects to gauge the feasibility of commercialisation. For example, the EU has renewed its commitment to funding further research and development of fuel cells and hydrogen technologies under the new Multiannual Financial Framework 2014-20. The FCH JU 2 has nearly 650 EUR m in grant money at its disposal over this period – 48% of which is dedicated to energy topics, including stationary fuel cells. All in all, the European diffusion projects remain much smaller in size compared to their international peers, which reflects some hesitance regarding the future of fuel cells compared to other alternative energy technologies. Furthermore, the technological know-how and number of fuel cell providers is still lower than overseas, due to the inexistence of comparable supporting schemes in Europe. As a result, European players in the fuel cell industry are at an earlier development stage and therefore tend to be less competitive. By funding the ene.field project, European policy makers have taken a concrete step towards commercialisation of stationary fuel cells – at least in the residential segment for fuel cell micro-CHP (mCHP) systems.

ene.field ¹³¹			
Country/region:	Europe	Objectives:	Measures:
Start:	2012		
Duration:	5 years	<ul style="list-style-type: none"> Field test up to 1,000 FC mCHP units Stimulate cost reduction by driving production volumes and commercialisation of FC-CHP technology 	<ul style="list-style-type: none"> Residential installation of 0.3-5 kW_{el} mCHP systems Deployment of mCHP units across 12 member states by bringing together 9 European mCHP manufacturers and 30 utilities, housing providers and municipalities
Amount:	53 m EUR		
Target Segment:	Residential	Results/status:	<ul style="list-style-type: none"> First two FC-CHP units installed in 2013 and two more in April 2014
Instrument type:	Grants		
Programme type:	Push		
Funded by:	Private, Public		
Key Learnings:			
<ul style="list-style-type: none"> Effective grant programme that initiates the first European roll-out of residential mCHP systems to gain practical performance experience from deployment in 1/2-family dwellings. Critical enabler for comparatively less mature European industry with strong focus on SOFC technology Beyond real-life learning on technology, effective programme to analyse the current supply chain, formulate homogeneous product specifications, and secure necessary stakeholders 			

Due to differences in the policy landscape amongst member states, commitment and support for innovative, alternative energies differs significantly. Thus, the roll-out of EU-wide support schemes for

¹³¹ Cf. ene.field (2014)

Fuel cells is fairly complex and potentially not feasible in certain countries. For this reason, a variety of country specific and even regional support schemes for alternative energies were introduced. We focus our overview on support schemes for stationary fuel cells in the chosen focus markets, primarily Germany, the UK and Italy.

Germany: Looking back on valuable experiences with stationary fuel cells

Within the EU, Germany has put in place the most extensive policy support for stationary fuel cell technologies – both at federal and at state level. Due to the country's decommissioning of its nuclear power programme, the need for alternative power generation – preferably from clean sources – is greater than ever. Moreover, a relatively large number of fuel cell technology providers are based in Germany and funding programmes help boost these companies' research and development efforts and accelerate the commercialisation of stationary fuel cells.

Callux ¹³²			
Country/region:	Germany	Objectives:	Measures:
Start:	2008		
Duration:	7 years	<ul style="list-style-type: none"> Gain insights about market entry and long-term commercialisation Collect test data for 2.9 m operating hours 	<ul style="list-style-type: none"> Deployment of 808 residential fuel cell units Testing of mCHP units under real conditions
Amount:	75 m EUR		
Target Segment:	Residential	Results/status:	<ul style="list-style-type: none"> Production cost savings of 60% and service cost savings of 90% since 2008 Over 2 m kWh_{el} produced from around 400 installed units in more than 3 m operating hours, one third CO₂ reduction for integrated fuel cell mCHPs measured on site
Instrument type:	Grants		
Programme type:	Hybrid		
Funded by:	Private, Public		
Key Learnings:			
<ul style="list-style-type: none"> Grant programme that analyses commercial feasibility of residential FC-mCHP systems through larger field tests and has achieved reputable results confirming commerciality of technology Roll-out delivers first larger sample in Europe of specific technical performance data for mCHPs, e.g. regarding measurable emissions savings (greenhouse gases, pollutants) 			

¹³² Callux (2014)

KWK Gesetz ¹³³			
Country/region:	Germany	Objectives:	Measures:
Start:	2009		
Duration:	11 years	Results/status:	<ul style="list-style-type: none"> • 5.11 EUR ct/kWh with funding for 10 years per CHP system <50kW • 2.1 and 1.5 EUR ct/kWh with funding for 30,000 hrs per 50kW_{el}-2MW_{el} and >2MW_{el} CHP systems
Amount:	8 bn EUR		
Target Segment:	All	<ul style="list-style-type: none"> • During temporary interruption of funding for CHP systems in 2010, new installations decreased by around 30% • Total of 426 TWh produced from CHP systems (ca. 5 bn EUR in tariffs) 	
Instrument type:	Tariff		
Programme type:	Push		
Funded by:	Public		
Key Learnings:			
Tariff law that effectively incentivises the use of CHP technology by improving the business case on the revenue side for the use of such systems through monetary compensation for every unit of electricity produced			

United Kingdom: Significant interest in CHP production

Next to Germany, the UK is also amongst Europe's dedicated supporters of alternative energies. The UK has set itself eager goals regarding the reduction of GHG emissions and expanding the share of renewable resources. Support schemes in the UK for clean energy technologies cover a wide variety of incentives including tariffs, grants and tax reliefs. Compared to other countries, a relatively large part of the UK's policy measures concentrate on the use of more energy efficient equipment, rather than specifically referring to the use of innovative and cleaner energy generation technologies. This is due to the UK's strong focus on heating in terms of energy consumed; the UK uses more energy for heating than for the generation of electricity or transport.¹³⁴ Consequently, the UK is likely to continue expanding its support for energy efficient heating technologies to tackle its goals of emission reduction and procurement of energy from alternative sources.

Renewable Heat Incentive (RHI) ¹³⁵			
Country/region:	UK	Objectives:	Measures:
Start:	2011		
Duration:	20 years	Results/status:	<ul style="list-style-type: none"> • Funding of 3,830 non-residential renewable energy installations • Fuel cell systems eligible only if powered by renewable source
Amount:	GBP 860 m		
Target Segment:	All	<ul style="list-style-type: none"> • Tariff scheme for non-residential applications started in 2011 and for residential applications in April 2014; intermediate results still pending • GBP 251 m budget for 2013-14 and increased to GBP 424 m for 2014-15 	
Instrument type:	Tariff		
Programme type:	Pull		
Funded by:	Public		
Key Learnings:			
A tariff programme to incentivise heating with renewable resources with limited government budget might lead to increased uncertainty in the market and may not be the most cost-effective programme to meet set objectives			

¹³³ Cf. Bundesrecht KWK 2002

¹³⁴ Cf. Department of Energy and Climate Change (2012)

¹³⁵ Cf. Gov.uk (2014)

Feed-in Tariff (FiT) ¹³⁶		
Country/region: UK	Objectives:	Measures:
Start: 2010	<ul style="list-style-type: none"> • Deployment of residential fuel cell mCHP with less than 2 kW_{el} amongst other technologies • Incentivise households to invest in low carbon micro-generation technologies 	<ul style="list-style-type: none"> • 4.5p/kWh paid for feed-in of domestic, renewable energy • Suppress price for mCHP units through decreased payback time or upfront cost
Duration: 11 years	Results/status:	<ul style="list-style-type: none"> • Consumer's energy bill savings of ~25% • Savings of 1-1.5 m tons of carbon per year • Over 470,000 installations of low carbon energy generation technologies until 2014; majority being solar photovoltaic (PV) systems – ca. 500 mCHP units
Amount: unknown		
Target Segment: Residential		
Instrument type: Tariff ¹³⁷		
Programme type: Pull		
Funded by: Public, Private		
Key Learnings:		
<p>Tariff programme that induces the residential use of low-carbon technologies, however, personal energy consumption, availability of alternatives, and specific user variables – such as socio-economic status – influence the willingness to install such technologies to a great extent apart from the improved business case for these technologies. Tariff levels must be set at the right level from the start and must be committed to for a significant period of time. In the case of the FiT, the PV tariff was set too high resulting in a rush for PV systems that could not be sustained. Subsequently, the rates were slashed causing a crash in the PV sector, subsequent leading to increased policy and investment uncertainty</p>		

Italy: Strong commitment to CO₂ reductions

Italy procures large amounts of energy from fossil fuels and is committed to raising the share of total energy demand coming from renewables to 17% by 2020. In comparison to other major EU states, this commitment is on the lower end. Concerning fuel cell technologies, Italy has so far implemented few schemes to directly support this technology. The only current support programme that exists is operating a total of three fuel cell mCHP systems in order to gain a better understanding of the technology and evaluate its commercial feasibility.

Tradable White Certificates ¹³⁸		
Country/region: Italy	Objectives:	Measures:
Start: 2005	<ul style="list-style-type: none"> • Reduce CO₂ emissions by incentivising use of cleaner energy production methods 	<ul style="list-style-type: none"> • Obligatory energy consumption reduction targets exist for firms • Every ton of oil equivalent (TOE) equals one certificate
Duration: 3 years	Results:	<ul style="list-style-type: none"> • Extended and revised scheme in 2007 • 3.7 m TOE saved between 2005-2008; exceeds target of 3.3 m TOE • 77% electricity, 19% natural gas and 4% other fuel savings
Amount: unknown		
Target Segment: All		
Instrument type: Trading		
Programme type: Pull		
Funded by: Public		
Key Learnings:		
<p>Trading scheme that was effective in offering static benefits (i.e. reduced emissions) during its active duration, but in Italy's case, failed to sustainably transform the market towards using more low-carbon technologies due to inadequate compliance with cost recovery rules; obligatory participation drove the early phases of this trading scheme</p>		

¹³⁶ Cf. Gov.uk (2014)

¹³⁷ Funded by increase in consumers' electricity bills, not by Government

¹³⁸ Cf. Giraudet & Finon (2011)

Overview of support schemes outside Europe

East Asia and North America are – by far – leading the way regarding support schemes for stationary fuel cell and CHP systems in terms of large-scale diffusion. The reasons for the advanced support of these technologies are many:

1. The larger share of technology developers are located in these regions and intensely collaborate with one another whilst benefiting from policy support across borders,
2. Regulatory frameworks in these countries mandate emissions reduction (often with tight regulation for local, not just global emissions) as well as renewable energy procurement targets, and
3. High-tech innovation is a hallmark of these regions.

Japan: Extensive experience with fuel cells for decentralised electricity generation

Japan pursues several fuel cell initiatives and perceives this technology to have great future potential. As a case in point, a nationwide roll-out of fuel cell mCHP systems in 1/2-family dwellings commenced in 2009 and is rapidly progressing. The suggested retail price for the mCHP unit has already decreased by ca. 43% with the introduction of the third generation model in 2013, making the units increasingly affordable. Additionally, the government has subsidised the roll-out of approximately 95,000 residential fuel cell heating units. These cost reductions reflect the coalition's anticipated learning curve included in this study. Lastly, Japan's research expenditures on stationary fuel cells exceeded USD 240 m in the fiscal year 2012 alone – more than twice the spending in the U.S. Due to the government's past involvements and commitment to propelling fuel cell technology, it can be assumed that support schemes will continue to prevail. In addition to generous investment support schemes, Japanese manufacturers of residential mCHP systems with fuel cells like Panasonic or Toshiba have benefitted from a particularly conducive market setting: Given the widespread institutional separation of electricity and gas utility companies in Japan, fuel cell manufacturers have successfully partnered with gas retailers to bring their products to the market. The retailers cross-subsidised the initial investment into the fuel cell by to long-term gas-sales contracts – an effective way to lower capital expenditure and positively influence the purchasing decision.

ene.farm ¹³⁹			
Country/region:	Japan	Objectives:	Measures:
Start:	2009	<ul style="list-style-type: none"> • Operation of 5.3 m ENE-FARM units by 2030 • Decreasing price for fuel cells through mass production 	<ul style="list-style-type: none"> • World's first home-use fuel cell system • Government subsidy for producing 5.3 m units
Duration:	6 years	Results/status: <ul style="list-style-type: none"> • Steady increase in units sold (20,000 by end of 2012) despite decreasing subsidy • Operating lifetime for FC increased from 50-60,000 hours due to improvements in PEM fuel cell installation leading also to lower unit costs 	
Amount:	80 m EUR		
Target Segment:	Residential		
Instrument type:	Subsidies		
Programme type:	Pull		
Funded by:	Public, Private		
Key Learnings: Subsidy scheme that effectively incentivises large-scale diffusion of residential CHP systems, thus driving production volumes which, in turn, lead to significant cost reductions and accelerate commercialisation of the technology			

¹³⁹ Cf. Fuel Cell Today (2013)

South Korea: Ambitious targets for fuel cells

South Korea is ambitious in reducing its GHG emissions and has defined strict goals under the Renewable Portfolio Standard (RPS). The country wants to reduce its energy dependence on fossil fuels, specifically its reliance on nuclear power. Seoul strives to supply 10% of its energy needs from fuel cells by 2030 and the government is funding ca. 60-70% of the projects necessary in achieving this goal. Additionally, a current milestone in the advancement of the fuel cell and CHP technology has been achieved in South Korea with the completion of the world's largest fuel cell park. This park consists of twenty-one 2.8 MW_{el} fuel cell units in series, equalling nearly 60 MW_{el} in total. It was constructed and operationalised in only thirteen months. In summary, South Korea is a pioneer in the development and deployment of stationary fuel cell technology.

Green Home Project ¹⁴⁰			
Country/region:	South Korea	Objectives: <ul style="list-style-type: none"> Promote the diffusion of new and renewable energy technologies in residential market Install 100,000 mCHP units by 2020 	Measures: <ul style="list-style-type: none"> Staggered subsidy for mCHP units: 80% in 2010 to 50% in 2020 Additional 10% subsidy from local government
Start:	2010		
Duration:	10 years	Results/status: <ul style="list-style-type: none"> Quick roll-out of systems – 1,500 mCHP units installed by end of 2012 already Ca. 200 MW_{el} of renewable energy technologies deployed in residential market by 2012 	
Amount:	unknown		
Target Segment:	Residential		
Instrument type:	Subsidies		
Programme type:	Pull		
Funded by:	Public		
Key Learnings: Staggered subsidy scheme that encourages deployment of low-carbon energy technologies in residential market in early stages, which leads to rapid cost reductions due to economies of scale from volume production early on			

Renewable Portfolio Standard (RPS) ¹⁴¹			
Country/region:	South Korea	Objectives: <ul style="list-style-type: none"> Make energy providers (>500 MW_{el}) procure 10% of their total output from renewable sources 	Measures: <ul style="list-style-type: none"> Providers can implement renewable sources or trade certificates; each MWh_{el} from renewables equals one certificate Fuel cells have highest certificate value in the trading system
Start:	2012		
Duration:	10 years	Results/status: <ul style="list-style-type: none"> Intermediate results still pending; review to be conducted in 2014 Meeting RPS targets largely depends on renewables to "reach grid parity" in levelled cost of electricity 	
Amount:	unknown		
Target Segment:	Industrial		
Instrument type:	Trading		
Programme type:	Pull		
Funded by:	Public		
Key Learnings: Trading scheme to increase energy suppliers' share of renewables by monetarily penalising emissions from use of fossil fuels, which is very effective in achieving set targets but leads to excessive operational costs due to complexity			

¹⁴⁰ Cf. KOGAS (2014)

¹⁴¹ Cf. Fuel Cell Energy (2014)

United States of America: Fuel cells as a part of the "all-of-the-above" strategy

The United States are determined to reduce their global emissions and to become a cleaner, more sustainable nation as a whole. Both on a state and federal level, policy makers are trying to advance the use of sustainable energy sources and decrease the U.S.'s dependence on fossil fuels. Consequently, the U.S. has launched several initiatives to promote the use of alternative energies. Especially fuel cell technology is supported by the federal government, due to the technology's perceived potential to reduce emissions and increase energy efficiency compared to conventional generation technologies. The U.S. aims to expedite innovation for the fuel cell technology to improve its commercial feasibility and induce a large-scale roll-out of fuel cell units. Moreover, the U.S.'s striving for fuel cell innovation is believed to increase job creation, making this endeavour more attractive from a political viewpoint. The following is a representative overview of the types of support schemes that exist in the U.S. for fuel cell and other clean energy technologies.

Feed-in Tariff ¹⁴²			
Country/region:	USA	Objectives:	Measures:
Start:	2008		
Duration:	12 years	<ul style="list-style-type: none"> Installation of min. 3,000 MW_{el} CHP systems in total to reduce 6.7 million metric tons (MMT) of GHG emissions For CHP units <20 MW_{el} 	<ul style="list-style-type: none"> Feed-in tariffs for CHP systems <20 MW_{el} and >62% efficiency CHP viewed as third most significant source for GHG emission reduction Tariffs will be available until cumulative capacity equals 750 MW
Amount:	750 MW		
Target Segment:	Industrial	Results/status:	<ul style="list-style-type: none"> Reduction of 1.61 MMT of GHG emissions; 3.19 MMT remaining More than 58% of MW_{el} capacity already installed
Instrument type:	Tariff		
Programme type:	Pull		
Funded by:	Public		
Key Learnings:			
Tariff scheme that successfully supports California in meeting its renewable portfolio standards through long-term diffusion of industrial CHP systems, but total incentives are limited by a maximum energy generation capacity			

Business Energy Investment Tax Credit (ITC) ¹⁴³			
Country/region:	USA	Objectives:	Measures:
Start:	2008		
Duration:	8 years	<ul style="list-style-type: none"> Encourage investment and growth in certain renewable energy and energy efficiency technologies 	<ul style="list-style-type: none"> Up to USD 1,500 per 0.5 kW_{el} installed capacity Fuel cells receive a 30% credit, CHP units 10%
Amount:	-		
Target Segment:	Com. & Ind.	Results/status:	<ul style="list-style-type: none"> USD 18.5 bn in tax credits have been issued under the Energy Investment Tax Credit as of May 2013, which equates to 9,016 approved credits Specifically, USD 160 m in credits have been distributed for FC and CHP systems
Instrument type:	Tax Credit		
Programme type:	Pull		
Funded by:	Public		
Key Learnings:			
Tax scheme that effectively incentivises commercial and industrial segments to invest in low-carbon technologies shortly after the recession, thus stimulating the economy and reducing national emissions simultaneously			

¹⁴² Cf. DSIREUSA (2014)

¹⁴³ Cf. DSIREUSA (2014), U.S. Department of Treasury (2013)

The U.S. Government's support for alternative energies, in particularly stationary fuel cells, will most likely continue in the future. The U.S. seem determined to defend their position as technology leader in this field. Furthermore, the pressure to grow clean energy and explore sustainable resources will remain high. Finally, the U.S.'s strategy has been to support a range of potential alternative energy technologies simultaneously. Until one technology proves to have clear advantages over the rest, the simultaneous support of multiple technologies will likely continue.

Key learnings from Chapter H (EXCURSUS)

- The ene.field project shows that grants can be a good instrument to gain practical experience and support commercialisation in large-scale demonstration projects
- Germany actively pursues commercialisation by undertaking larger demonstration projects such as Callux for residential mCHP systems
- CHP tariffs are a suitable tool to promote CHP technology, as the experiences in Germany and the United Kingdom make clear
- The Japanese experience with investment subsidies for residential mCHP system (ene.farm) shows the strong technological and commercial improvements that can be achieved under such funding schemes if applied at large scale
- The United States chose a commercialisation policy approach based on investment tax credits

I. Recommendations

The section above highlighted several hurdles that need to be addressed by industry and policy makers in order to render the commercialisation of the stationary fuel cell successful. The first part of this chapter derives general recommendations to these specific stakeholders on the basis of the barriers discussed in Chapter G. The consolidated results are presented in Figure 105. The second component of this section outlines specific recommendations to stakeholders within the three commercial segments of this study (residential, commercial and industrial).

Strategic recommendations: Emphasise the business model and avoid low impact technology specific improvements

The benchmarking in Chapter E identified significantly higher capital costs associated with the stationary fuel cell in comparison with competing technologies. In terms of operational expenditure, the fuel cell is highly competitive already today, due to a favourable spark spread in several European markets. The high capital cost is the greatest obstacle to the commercialisation of the fuel cell in Europe. We therefore encourage industry members to make capital cost reduction the highest priority on their R&D agenda and to pursue ambitious near-term targets for cost reduction. Fully aware that the economic performance hinges on production volumes, it is advisable to implement revenue and financing models that exclude a high initial investment for the consumer and extend revenues over the lifetime of the fuel cell module. This will facilitate market entry considerably. Policy makers are encouraged to support the development and deployment of stationary fuel cells for CHP financially on a temporary basis, in order to accelerate sales, and deliver on production targets. Furthermore, support schemes and other economic policy measures should be aligned on a European level in an attempt to stimulate the development of standardised stationary systems.

This study identified several shortcomings on the technical side that ought to be addressed.

Primarily, the average stack degradation rate still has considerable room for improvement as well as lifetime, efficiency and overall robustness. We recommend that the industry address these issues with the utmost consideration for the stability requirements of the end user, and emphasise improvements in this area on their R&D agenda. Policy makers are encouraged to make financial support for R&D available, given the relevance of these components. In-field projects offer great potential to develop key learnings which translate into technological improvements. Therefore, we encourage industrial stakeholders to seek out opportunities for demonstration projects, and policy makers to support these undertakings financially.

Furthermore, we recommend players on the brink of full-scale commercialisation to pursue lean production methods with a higher degree of automation. Primarily, it is important to reduce scrap rates by automating key production steps such as printing, cleaning and stacking. Efficient organisation of the production process and a higher utilisation of the available machinery will optimise the work flow. These steps could lead to an increase in batch sizes, whereby set-up times and the direct labour costs can be reduced. The stack sintering was identified as a potential bottleneck in the production process of SOFC stacks, due to the long duration of the process and its energy intensity. We recommend targeting efforts at the resolution of this problem. Continuous improvement of the production process should also include efficient and effective quality management.

The configuration of the value chain revealed that suppliers of materials and components as well as stack suppliers often only perform single highly specialised steps in the value chain.¹⁴⁴ Standardising the production of stacks and reducing the dependency on single suppliers and the risk of unforeseen supplier exits represents an important step in the successful commercialisation of the fuel cell. Therefore, we recommend the establishment of standard setting organisations for suppliers and system integrators. On the one hand, the latter may serve as a platform for knowledge sharing and the identification of best practices. On the other hand, it facilitates commercialisation by spurring standardisation of key components. Furthermore, we encourage manufacturers to integrate additional value-add steps into their product portfolio in order to secure the supply chain. The latter could also be achieved by creating and maintaining strategic partnerships with downstream suppliers. Policy makers are encouraged to continue and expand an inclusive industry dialogue. Furthermore, a clear commitment to the fuel cell technology by policy makers inspires investment security and thereby aids the producing industry in securing financing.

It is important to pursue cost reductions along each stage of the value chain, therefore the role of sourcing is critical. On the one hand, competitive sourcing will require an advanced degree of standardisation from suppliers. On the other hand, system developers in particular can push for price reductions with suppliers by anticipating cost degressions correctly and negotiating contracts on the basis of these projections. We recommend policy makers monitor the industrial production process closely and assign funds in accordance with pre-defined industrial cost and production targets.

In terms of market access barriers, Chapter C identifies path dependency for conventional heating solutions in the consumer decision, and a general lack of awareness of the fuel cell as potential obstacles to commercialisation. Chapter F derives the necessity of seeking new partners in order to build a comprehensive Go-2-market strategy. OEMs should therefore seek cooperations and partnerships with planning, engineering and consulting offices. Thereby, it is possible to consolidate and leverage the customer base and offer comprehensive CHP solutions. Furthermore, particularly in the residential segment, installers have an important local footprint and are key players at the customer base. On the one hand this means that accessibility may be somewhat restricted due to existing business relationships, reinforcing the path dependency outlined above. However, collaboration with installers can prove to be a highly promising business model for both sides, which is why we recommend partnerships in this area. The potential for alternative Go-2-market partnerships, such as with utilities, should also be extensively explored. In order to increase the general awareness of the stationary fuel cell technology, we encourage stakeholders to educate Go-2-market partners extensively and rally their support in communicating the technology benefits to the customer. We encourage policy makers to campaign in support of favourable market conditions, emphasising the benefits of combined heat and power production and the favourable environmental performance of the fuel cell. This message is particularly relevant to urban areas, where air pollution represents a paramount problem requiring attention from regional policy makers.

The acceptance barriers identified above revolve around the incomplete availability of credible and convincing product and technology information to the customer. Therefore, it is important to communicate the success stories of demonstration projects clearly and extensively and to perform projects in locations with a very high visibility, particularly in the commercial sector. Marketing campaigns may prove valuable to those players active in the residential segment, in order to create a pull effect for the fuel cell. Policy makers can play an important role in lowering access barriers by displaying public commitment to the technology and communicating the benefits to the general public.

¹⁴⁴ For additional information, please refer to Chapter F

With regard to regulatory hurdles, the stationary fuel cell industry in Europe requires a reliable regulatory framework that is supportive of (distributed) CHP technologies and that places emissions savings as well as reduced primary energy consumption at the heart of energy legislation. In this regard, immediate need for action concerns – for example – the introduction of a compulsory EU Energy Label for heating technologies which duly considers primary energy savings of micro-CHP units through a proper methodology that is reflective of the performance of the product in terms of primary energy consumption. Moreover, we encourage the industry to lobby for tighter restrictions on urban emissions, given the preferable emissions balance of the fuel cell in terms of CO₂, but also concerning pollutants and particulates. This point is highly relevant to policy makers, especially on a regional level. In order to compete economically in the short term, fuel cells will predominantly seek to take advantage of the extensive gas grid infrastructure available across the EU. A long-term environmental strategy embracing the decarbonisation of the gas grid will support the sustained roll-out of fuel cells in future by allowing them to continue to utilise this infrastructure whilst at the same time reducing their emissions and maintaining their current environmental advantage over competing technologies even as the EU electricity grid decarbonises. We encourage policy makers to include this approach in their agenda and also further promote sustainable biogas production from renewable sources. At the same time, industry players need to ensure their fuel cell system's compatibility with a greener gas mix that may include larger shares of biogas, hydrogen as well as synthetic natural gas.

	Industry	Policy makers
Economic barriers	<ul style="list-style-type: none"> > Push for achieving cost reduction targets > Pursue new revenue and financing models (esp. contracting and leasing offerings) 	<ul style="list-style-type: none"> > Put in place temporary financial support schemes, such as investment or project-based support > Align relevant existing policy measures
Technical barriers	<ul style="list-style-type: none"> > Deliver on ongoing demo projects and field tests > Tackle main technical challenges (esp. stack durability, overall robustness, efficiency) 	<ul style="list-style-type: none"> > Fund further R&D on critical technical paths > Expand support for demonstration projects and field tests across all segments
Supply chain barriers	<ul style="list-style-type: none"> > Initiate industry collaboration for standard setting > Join forces along the value chain to offer full DG solutions, e.g. with engineering firms 	<ul style="list-style-type: none"> > Demonstrate and communicate commitment to stationary fuel cells > Continue and expand industry dialogue (VC, G2M)
Market access barriers	<ul style="list-style-type: none"> > Seek new partnerships in Go-2-market, e.g. for sales force and service capabilities > Educate existing Go-2-market players 	<ul style="list-style-type: none"> > Maintain current CHP support and prevent erosion via conflicting regulation > Remove obstacles to innovative financing
Acceptance barriers	<ul style="list-style-type: none"> > Raise awareness with end users to create pull effect > Disseminate results of prototyping, demo projects and field testing 	<ul style="list-style-type: none"> > Campaign for benefits of the fuel cell, particularly in terms of emissions and energy savings
Regulatory hurdles	<ul style="list-style-type: none"> > Lobby for tighter regulations on local emissions > Communicate and lobby environmental benefits of fuel cells 	<ul style="list-style-type: none"> > Commit to the decarbonisation of the gas grid > Reform eco-labelling at EU level > Tighten local emissions regulations

Figure 105: Strategic recommendations across segments to overcome barriers to commercialisation

Segment-specific recommendations: Advancing commercialisation in the three market segments with mutual commitments between industry and policy

Segment specific recommendations towards commercialisation can be derived by looking at the learning curve effects of each technology cluster and comparing the total annual heating cost as well as the relevant price levels to other competing technologies. A fundamental assumption is that once economic competitiveness is reached the fuel cell technology becomes self-sufficient. The following recommendations are based on the idea that this state needs to be reached in order to exploit the advantages cited above. However, we generally propose a mutually binding commitment between industry and policy. Industry needs to deliver the cost reductions at relevant production volumes whilst

policy commits to make these production volumes possible. Policy funding must thereby be subject to target realisation, i.e. if learning curve effects are not reached funding should be stopped or if learning curve effects are reached funding should be stopped as well.

Figure 106 gives an overview of the support scheme approach we recommend based on the analysis conducted in the course of this study. In order for the fuel cell to become an integral part of the energy system, it is important to catch up with prevailing technology alternatives in terms of cost, reaching a new price segment in each step of the commercialisation process. Cost reductions as anticipated by the industry are explored in detail in the analysis above. The steep learning curve projections imply that initial funding for the industry is necessary but should phase out as commercialisation progresses. In consonance with this line of thought, policy makers are encouraged to tie funding to the achievement of cost reductions as projected by the industry.¹⁴⁵

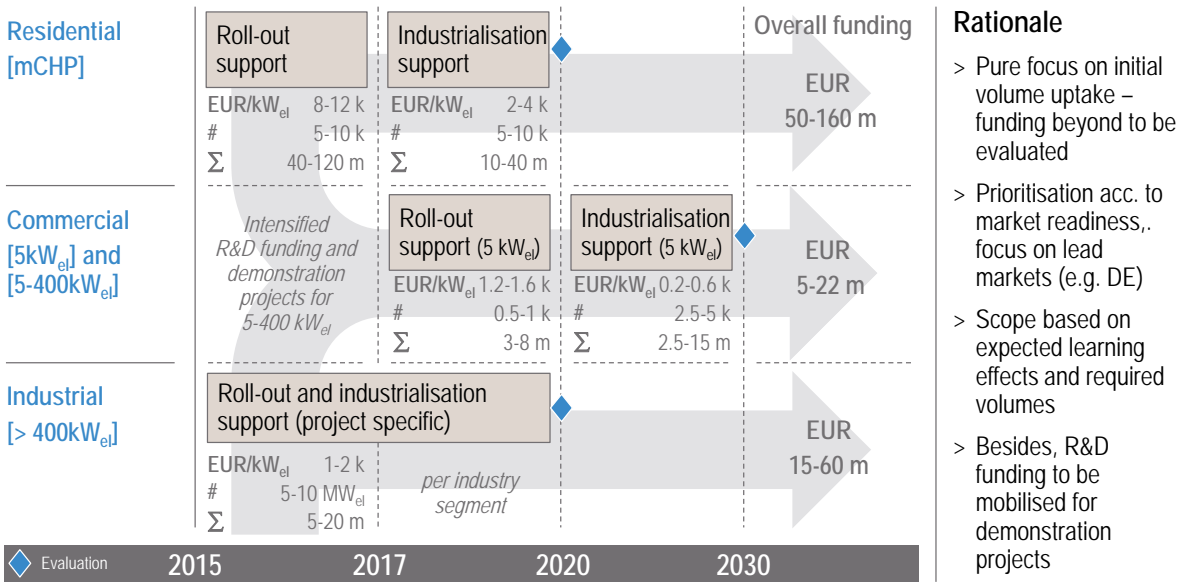


Figure 106: Potential framework for segment-specific investment support for commercialising stationary fuel cells

We give segment-specific recommendations for supporting commercialisation that focus on generating volume uptake for the industry in order to achieve volume-driven cost reductions. Public R&D funding is not explicitly in the scope of our proposed funding efforts. However, R&D priorities should be defined for and tied to demonstration projects that are supported with public R&D funds (e.g. by the FCH JU under Horizon 2020), especially in the commercial segment that features the least market readiness as of today. We define funding priorities according to the market readiness of different segments, placing immediate emphasis for market introduction programmes on fuel cell mCHPs as well as project-based financing for industrial applications. The funding scope (sums and volumes) is based on expected learning effects and required production volumes as analysed by this study (please see Chapters D and E). The funding should be limited to the number of units needed to achieve necessary cost reductions. For the individual market segments and associated stationary fuel cell systems, we specifically recommend the following.

We stress that the proposed framework should be seen as a first, volume-focused public funding framework, i.e. a segment-specific subsidy scheme that is limited in time and scope. It should be seen as the start of a European market introduction program whose continuation should be subject to close

¹⁴⁵ For a detailed analysis of cost reductions over time and volume, please refer to the benchmarking chapter.

performance monitoring of the industry – particularly further evaluation of the industry's performance against cost reduction targets.

Recommendations concerning fuel cells targeting the residential segment

In order to reap the substantial benefits in terms of higher energy efficiency, lower emissions and accelerated distributed generation, fuel cell system providers and stack suppliers that are already on the brink of commercialisation need public support in the roll-out phase – as a targeted measure to build a bridge towards market introduction. Provided that the industry successfully delivers on ongoing demonstration projects, such support schemes should be implemented – however clearly limited in time and scope. Policy makers should closely monitor performance and cost improvements. We recommend 8,000-12,000 EUR/kW_{el} support for units deployed in the residential segment. Support should be made available for the deployment of 5,000 to 10,000 units in this segment, amounting to total funding of 40 to 120 m EUR. During this phase, the stationary fuel cell could become economically competitive with high-end technologies on the basis of Total Cost of Ownership, i.e. heat pumps and engine-based CHP technologies. After the roll-out phase, we recommend making further funds available depending on the achievement of pre-defined cost targets that are to be regularly monitored by the corresponding policy authorities. In order to support industrialisation in this segment (which industry experts project to commence in 2017) support of 2,000-4,000 EUR/kW_{el} for 5,000- 10,000 units would be needed. The overall financial requirements for the residential segment amount to 50-160 m EUR. During the industrialisation phase, stationary fuel cells for the residential segment may achieve significant cost reductions and establish themselves amongst competing solutions – laying the foundation for deployment at mass-market scale. Given the decreasing emissions savings attributable to the fuel cell as Europe's power mix decarbonises, we encourage the funding to be made available to the industry following this temporary funding scheme and as soon as possible.

Recommendations concerning fuel cells targeting the commercial segment

The commercial segment has high potential as a market for stationary fuel cells. However, considerable policy support is needed in order to spur the development of viable concepts for commercialisation, i.e. further R&D. We recommend policy makers to make funds available for additional demonstration projects in order to support the industry in developing prototypes, proving the technology in-field and disclosing the progress to commercial decision makers. However, before funds can be granted the commercial segment must significantly learn from the other segments to reach a viable starting point. At this point in time, the only conceivable subsidy framework aiming at volume-uptake for systems in the commercial segment includes the niche of 5 kW_{el} CHP systems for centrally heated apartment buildings; larger CHP systems between 5 and 400 kW_{el} have yet to demonstrate market-readiness. To the contrary, 5-kW_{el} systems take part in e.g. the ene.field project, even though suppliers are not ready to deliver products to the extent that mCHP OEMs already can. The roll-out phase for the commercial segment is thus assumed to follow the roll-out of the residential segment with 5 kW_{el} taking the lead. We expect the industry to have greater commercial success by benefiting from spill-over effects from the residential segment, specifically, lower costs from suppliers and a higher degree of stack standardisation. Overall, we encourage policy makers to consider committing 1,200-1,600 EUR/kW_{el} support during any future roll-out phase funding 500-1,000 units of 5 kW_{el} CHP systems. During this phase, stationary fuel cells in the commercial segment have the opportunity to become economically competitive with heat pumps, establishing themselves amongst high-end heating technologies. Conditional on the achievement of pre-defined cost targets, funding could further be made available for 5 kW_{el} CHP systems in a second phase. This support should specifically be dedicated to achieving industrialisation, with 200-600 EUR per kW_{el} support for 2,500 to 5,000 units. Given the promising results of the environmental and economic benchmarking exercises in larger commercial use cases

(office building, shopping center, hospital), we encourage funding authorities to intensify funding of demonstration projects to validate the technical and economic viability of 5-400 kW_{el} CHP fuel cells in such use cases – comparable to the Topic FCH-02.5-2014 " Innovative fuel cell systems at intermediate power range for distributed combined heat and power generation" under the 2014 FCH JU Call for Proposals.

Recommendations concerning fuel cells targeting the industrial segment

There are several good experiences with stationary fuel cells for power generation in the industrial segment. The benefits of the technology are outlined extensively in the benchmarking chapter. In terms of recommendations, we believe that players within the industrial segment should require additional references in the European market in order to promote the technology image in the market for auto-generation. We encourage policy makers to make funding available for projects involving appliances greater than 400 kW_{el} and to commit 1,000 to 2,000 EUR per kW_{el} in policy support. Funding should focus on specific industry applications, because consistency in the type of application reduces complexity and improves learning potential due to the comparability of results. Funding should thereby be sufficient to help existing players with marketable products to reach learning curve effects. The first main step is thereby reached at around 5 to 10 MW_{el} cumulative production volume per company. Focus industries should be selected according to a proper evaluation. Funds shall be committed accordingly, e.g. if three focus industries are selected an equivalent of 15 to 30 MW_{el} cumulative installations should be funded. The number of funded installations should match the number of players in a way that learning curve steps can be reached. However, if learning curve effects cannot be realised – despite sufficient volumes– funding should be stopped in the respective industry. In order to make the benefits of the fuel cell CHP visible to industrial decision makers, it is important for fuel cell representatives and policy makers to choose projects with high visibility and communicate benefits clearly and exhaustively.

Furthermore, the industry should lay particular emphasis on means of automating production processes and improving stack robustness and durability on the back-end side. Regarding policy commitment, we support the introduction and extension of CHP production premiums. Past experiences, particularly in Germany, have shown that CHP premiums are a purposeful and goal-oriented means of encouraging the deployment of efficient CHP technology. Moreover, this policy measure is highly visible to industrial customers and signals political support. We regard the industrial segment to be very noteworthy on a European level; however, there is still great room for improvement in the production process, value chain configuration and go-to-market strategy.

The recommendations are solely concerned with commercialisation and do not take into account that some fields need other support measures, e.g. the commercial segment will need to engage in further research and development to develop systems in the range of 5 to 400 kW_{el} that could actually serve the given market needs. Moreover, the recommendations are drawn under the assumption that other factors remain rather stable. Assuming that the actions are taken we believe that two possible pathways of development are viable. Either the fuel cell positions itself as high-end niche market technology with specific characteristics and advantages or it positions itself as a mass-market technology outperforming today's standard solutions. The potential development pathways are described below.

Market outlook: The commercialisation of stationary fuel cells in Europe depends on initial policy support

The market diffusion of fuel cell systems depends on many segment-specific factors. It appears rather obvious that the technology cannot gain traction in terms of larger scale market diffusion all by itself, given the fact that competitive pricing may only be possible through higher production volumes. A vicious cycle in this regard is apparent today and may last as long as external support does not push forward industrialisation. We believe that the market needs a chance to demonstrate that it can achieve further significant cost reductions and may eventually reach competitiveness. However, if the market proves unable to deliver sufficient price reductions, stationary fuel cells will continue to struggle to become self-sufficient. Then, further support programmes should end accordingly and the market will hardly develop further. However, if cost degression targets are reached, the market has significant potential. In this line of thought, we see two potential pathways, illustrated in Figure 107 below: one where fuel cells become a high-end niche technology such as the heat pump in the residential heating market today and another pathway where fuel cells become a mass-market solution and substitute today's standard applications such as gas condensing boilers. Although the fuel cell incorporates many advantages over other technologies and user decision chains are multi-dimensional, we believe that fuel cell success can only be assured by competitive price levels.

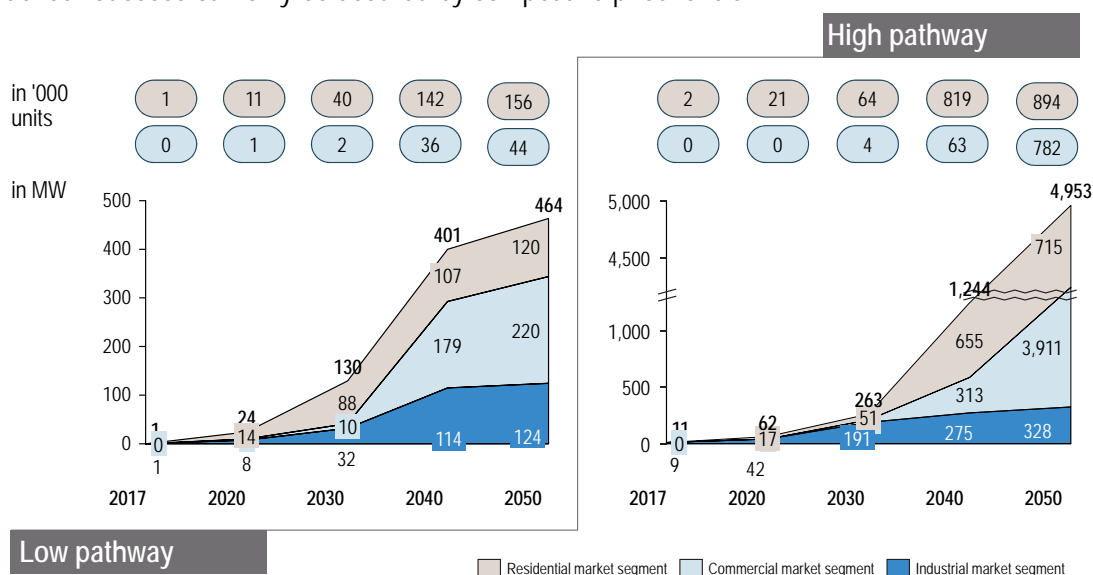


Figure 107: Potential pathways for market diffusion of stationary fuel cells in Europe

In terms of the macroeconomic scenarios outlined in Chapter B, we consider the low pathway more likely to emerge in the context of a European energy system that resembles the "Patchy Progress" scenario leaning towards the "Untapped Potential" world. In contrast, the high pathway for diffusion of stationary fuel cells in Europe may be more likely in the frame of the "Patchy Progress" scenario leaning towards the "Distributed System" energy landscape.

The residential fuel cell market will probably develop most rapidly out of all three market segments because it is the most mature and mass-oriented segment. Given a funding programme as proposed above we estimate that the market will develop along funding lines, i.e. the market volume will equal the amount of available funding in Europe. For both development pathways, we assume that funding of fuel cell mCHP systems will continue until cost parity of the technology versus alternative (CHP) heating systems is reached. If such funding occurs, we anticipate an annual installation of one to two thousand fuel cell mCHP systems by 2017, resulting in the first major cost reduction step. With continued funding up to 2020, around 10-20 thousand fuel cell mCHP systems could be installed

annually. The second projected cost reduction step concludes funding for fuel cell mCHP systems, which should thereby reach cost parity with other (CHP) heating systems. In the best case scenario, fuel cell mCHP system installations will increase rapidly – due to greater technology efficiency compared to alternatives and continued CAPEX reductions. If the fuel cell cannot achieve further cost reductions by then, we estimate that the market volume will reach a stable market share comparable to the heat pump and other CHP systems. CAPEX for CHP systems in general will thus remain higher than for other gas heating solutions, such as boilers, in the long run. CHP (incl. fuel cell) systems are forecasted to reach eight percent market share by 2040, which amounts to ca. 142 and 155 thousand annual fuel cell mCHP installations in 2040 and 2050 respectively.

There is significant upside potential in the event of the fuel cell hitting a level below the annual energy cost of a boiler solution. For the years 2030, 2040 and 2050, we believe that annual installations of 64,000, 891,000 and 893,000 units respectively can be possible. FC systems may capture and maintain a 40% share of the addressable market for annually installed gas systems. This equals ca. 20% of the overall annual addressable market for new heating systems by 2050 under the given assumptions.

The commercial segment is split into two parts, the smaller 5 kW_{el} and the larger 50 kW_{el} systems. Since the industry's product offering for 5 kW_{el} fuel cell CHPs is currently very limited, we believe that the market introduction for this model should be postponed until these units reach the same maturity as fuel cell mCHP systems in the residential segment. This may take as long as the demonstration period in the residential segment, i.e. another five years. During this period commercial systems must learn from residential systems to bridge the large price gap between segments. We thereby believe that only if these learning spill-overs are achieved does funding become a viable option. Funding for 5 kW_{el} fuel cell systems would then commence around 2019/2020 and proceed similarly to the funding in the residential segment. Consequently, in 2020, three to six hundred 5 kW_{el} fuel cell CHP systems will be installed depending on the number of players in the market and the given funding sum. Once the second cost reduction step has been reached for 5 kW_{el} FC systems, which is projected to occur around 2025, TCO parity versus other CHP options will ensure the competitiveness of the fuel cell technology. If 5 kW_{el} fuel cell CHP systems continue to coexist in the CHP market, we estimate that fuel cell CHP will become cheaper than other CHP alternatives shortly after 2030. If the FC system cannot further decrease its price level it can be assumed that it will position itself as a high-end CHP solution competing with the engine-based competitors. Therefore, kW_{el} fuel cell CHP systems would become a niche product and annual installations would be around 36 and 44 thousand in 2040 and 2050 respectively. Large-scale diffusion in the commercial segment will only be possible if TCO falls below that of the gas condensing boiler. In that case, however, the commercial market segment may grow to be the largest segment in the market in terms of installable capacity. The increasing market share of 5 kW_{el} fuel cell CHP systems and a steadily growing market for gas heating solutions could lead to ca. 780 thousand new 5 kW_{el} fuel cell installations annually. Analogous to the development of fuel cell technology in the residential segment, we assume that 5 kW_{el} fuel cell CHP systems could then comprise 40% of the addressable gas market by 2050, which equals ca. a quarter of the total addressable heating market.

The market development for the larger, 50 kW_{el} commercial fuel cell CHP systems is dependent on spill-over learning effects from 5 kW_{el} systems. Since the TCO of 50 kW_{el} fuel cell CHP systems is currently far above that of alternative (CHP) heating systems, there would have to be an extremely cost-intensive funding scheme to make 50 kW_{el} fuel cell CHP systems competitive. We presume that such vast funding measures for these systems will not exist, especially due to prior funding of residential and 5 kW_{el} fuel cell CHP systems, as mentioned above. Consequently, 50 kW_{el} systems must develop when the fuel cell market has grown mature and may therefore evolve after 2030.

The industrial segment is dominated by on-site generation, which has gained significant importance over the last years partially due to higher electricity prices, efficiency and power security orientation. A simplifying assumption has been made, namely that the annual addressable market for new heating installations remains constant. Across all industrial applications, the annual addressable market size for new heat installation is around 770 MW. The current TCO difference between FC systems and other gas-based systems can only be levelled with the help of funding projects during the initial stages in both the best and worst case scenario. Without this funding, the industrial segment might become impenetrable for the fuel cell technology. If funding occurs, however, we estimate that around 9 MW_{el} of fuel cell systems (of which 6 MW_{el} are CHP and 3 MW_{el} are prime power) are likely to be installed in industrial applications by 2017. Thereafter, TCO parity could be reached between 2017 and 2020 and the annual installed MW_{el} capacity would be around 42 MW_{el} (32 MW_{el} CHP) and 28 MW_{el} (18 MW_{el} CHP) for the higher path and lower path in 2020 respectively. By 2030, the annual FC system installations could grow to 191 MW_{el} (142 CHP) and 104 MW_{el} (62 MW_{el} CHP), assuming a TCO advantage over most alternatives; although the gas motor is always presumed to have a cheaper TCO than fuel cell systems. Nonetheless, FC systems can continue to enlarge their TCO advantage compared to the majority of heating alternatives and consequently gain increasing market share. This trend is predicted to prevail at least until 2050. Thus, in 2040 we estimate the annual installed FC capacity to be 275 MW_{el} (190 CHP) and 169 MW_{el} (98 MW_{el} CHP) in the upper and lower pathway scenario respectively. By 2050, the rate with which fuel cell systems capture market share from competitive technologies will recede.

In general it appears that residential and industrial markets will serve as "front runners" for diffusion and may thus capture most of the initial government support funding that is dedicated to actual commercialisation. In turn, these segments must carry the responsibility to deliver functioning, efficient and particularly cheaper systems. Other market segments will pick up afterwards and will hold significant potential for industry players to diversify and internationalise. Clearly, the successful commercialisation will continuously depend on the policy framework in place, e.g. to what extent it remains favourable to distributed generation and cogeneration. However, if price targets are reached it is still subject to many open questions. Some are answered by this study; others need to be answered by action. Therefore market development remains ambiguous and subject to the actions taken by industry players as well as policy makers.

Key learnings from Chapter I

- The industry needs to bring down capital cost; technical barriers, particularly regarding stack durability and robustness, need to be addressed
- The value chain should pursue higher standardisation of key non-IP components
- Policy support for fuel cells can spur awareness and public support for the technology, funding should be made available to the residential segment for customer investment support
- System providers in the commercial segment need to capitalise on benefit from spill-overs from the residential segment; companies in the industrial segment should pursue visible demo-projects with public funding
- In terms of the market outlook, the commercialisation of stationary fuel cells in Europe has to rely on initial policy support. Depending on the favourability of the policy framework and the industry achievements in terms of cost reduction and sustained performance, we expect either a niche-market or a mass-market scenario for market diffusion

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