Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies

FCH contract 192

Evidence Report

E4tech (UK) Ltd for FCH 2 JU in partnership with Ecorys and Strategic Analysis Inc.

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Contents

List of figures

List of tables

1 Introduction

1.1 This 'Evidence' report

The outputs of this study are divided into three reports:

- A 'Summary' report that provides a synthetic overview of the study conclusions;
- a 'Findings' report that presents the approach and findings of the study;
- and this 'Evidence' report that provides the detailed background information and analysis that supports the findings and recommendations.

Some material used in the 'Findings' report is also included here for completeness.

1.2 Context and background

Fuel cells and hydrogen (FCH) could bring significant benefits across the energy and transport systems, enabling low carbon, zero air quality emissions options, and efficient energy conversion. Whilst these benefits may be achieved irrespective of the geographical origin of the technologies used, the benefits to Europe could be greater if the European industrial supply chain for fuel cells and hydrogen were to play a strong role. These benefits could be:

- *Economic*: as an expanding area for green growth, generating revenue for European countries and creating highly skilled jobs in a knowledge-based sector;
- *Environmental*: through ensuring that the technologies developed are appropriate for European markets, that they are available for European deployment when required, and because there may be greater willingness to promote and support deployment of European technologies in Europe.

FCH technologies are sometimes seen as competing with other emerging solutions to environmental and economic problems, such as battery electric vehicles (BEVs). As BEVs are in a more advanced state of manufacturing development and deployment, more analysis has been conducted on their national and international value proposition. More rigorous evaluation of FCH technologies is providing information and data against which to compare these and other technologies and sectors.

FCH 2 JU is a public-private partnership between the European Commission, European industry and European research organisations, and supports research and technology development (RTD) activities in FCH technologies in Europe. Recognising the potential benefits from a strong FCH supply chain in Europe, and the opportunities for initiatives to support new energy supply chains, FCH 2 JU commissioned and received a preliminary analysis of the FCH sector and its supply chain status in 2017. This study examined a subset of applications and primary actors, as well as providing initial inputs on potential areas of strength and weakness for Europe. The FCH 2 JU has commissioned this study as an in-depth follow-on analysis. It looks at more applications, in more detail, not only at the supply chain opportunities and threats, but also at the broader value chain. This piece of work has produced a more comprehensive database and provides recommendations for actions that can be taken to support the successful growth of a European supply chain.

While Europe has a very strong research and technology base, and strong supply chain actors in some areas, Japan, Korea and some parts of the US have been the early movers in the actual deployment of fuel cell and hydrogen technologies, and they are now being joined (and are likely to be overtaken) by China. National industries and initial supply chains have begun to evolve. Apart from in the US, FCH technologies in these regions are supported by a clear vision to build a local industry to serve the domestic market, and eventually to become a leading exporter of these new technologies when other world regions embrace FCH. Policies such as the Clean Energy Manufacturing Initiative in the US, the New and Renewable Energy Portfolio Standard in Korea and the Ene-Farm programme in Japan represent some of these efforts to build national markets and industries. And although high volume deployment has not taken place in Europe so far, the European FCH industry has profited from the deployments in the US, Korea and Japan: the major system integrators serving those markets rely on a global supply chain including many European actors; and some technologies developed overseas have been re-engineered to local standards and conditions and integrated into the product lines of European suppliers for sales in Europe.

The European FCH sector is very diverse but well interconnected (partly thanks to the significant activities of the FCH 2 JU). Some European countries have mapped their own fuel cell and hydrogen industry and knowledge-based actors (e.g. Fuel Cell Industry Guide Germany 2016 [1], Hydrogen and Fuel Cells: Opportunities for Growth – A Roadmap for the UK[2], Swiss Hydrogen & Fuel Cell Activities: Opportunities, barriers and public support[3]). In contrast, this study systematically looks at selected full value chains and manufacturing competitiveness at a European level, which has not been done before. While the global and European market for these technologies is still small, it is growing rapidly and expected to continue to do so. Now is the right moment to secure a leading role for Europe. To do this, targeted interventions may be necessary, and these can be informed by thorough analysis of the European supply chain and knowledge base, and a clear view of their strengths and weaknesses, put in the context of the opportunities to be grasped.

The FCH 2 JU's overall objective for this study is to assess the contribution that the FCH sector could make to green growth in Europe, as well as to climate and energy goals, and to make recommendations to political and other actors on how to maximise this contribution. This study thus has several main functions:

- To provide a database of actors in the European supply chain, from which useful data and information can be extracted, and with the potential to be updated on an ongoing basis;
- To provide a view on the most valuable or most fragile parts of the value chain, from an economic and strategic perspective and in a global context, including with respect to important competing alternatives;
- To develop plausible scenarios for the role of the FCH sector in Europe that give all interested parties a common understanding of the opportunity;
- To provide robust analysis of the value that the sector could bring to Europe, high quality supporting data, and rigorous recommendations that can be used to further develop and support the European FCH sector.

1.3 Study objectives

The objectives are:

1. **In-depth analysis and updated mapping of industrial actors in European FCH supply chain** for a number of applications in the transport and energy sectors, including the manufacturing supply chain, to provide a clear view of the composition, structure, and level of activity in the European FCH sector today;

[1] Fuel Cell Industry Guide Germany 2016 https://www.vdma.org/en/article/-/articleview/13175963
[2] E4tech Development of a roadmap for hydrogen and fuel cells in the UK to 2025 and beyond. Report published at http://www.e4tech.com/wp-content/uploads/2016/08/HFCroadmap-MainReport.pdf
[3] E4tech Assessment of the Swiss hydrogen and fuel cell sector, Report published at http://www.bfe.admin.ch/php/modules/enet/streamfile.php?file=000000011234.pdf&name=000000290993

2. **In-depth analysis and updated mapping of the European FCH knowledge-based actors**, such as research centres and universities that contribute to the same European FCH supply chains today, or with potential to contribute in the future, in order to provide a view of the level and type of knowledge-based activity;
3. **Value chain and manufacturing competitiveness analysis**, identifying the parts of the supply chain of greatest value at component level for transport and energy applications, the capabilities of supply chain companies and European research in comparison with global competition; and bottlenecks and barriers to the successful exploitation of these opportunities for Europe;
4. **Development and assessment of potential scenarios for the European FCH value chain and manufacturing competitiveness to 2024 and 2030**, including detailed global and EU deployment modelling, evolution of the future competitiveness of European supply chains, and quantified scenario impacts;
5. **Recommendations for specific actions and investments**, providing a set of actions at component and application level, and for the European sector as a whole, which could improve European competitiveness and value creation.

1.4 Approach overview

The project approach is summarised in Figure 1 below:

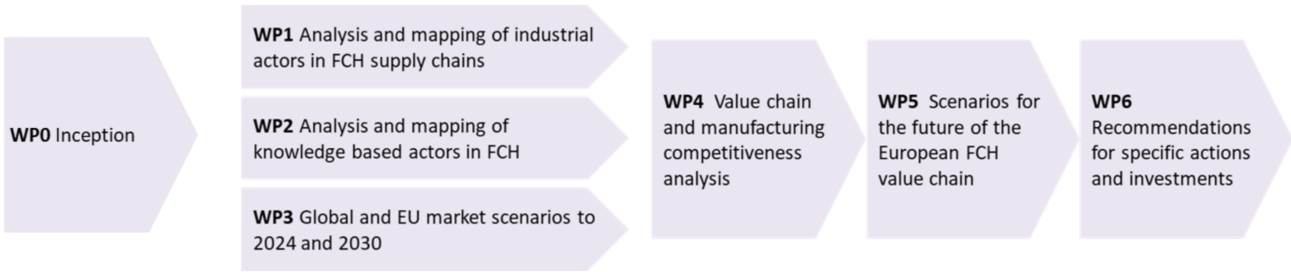

Figure 1: Project approach

These work packages consist of:

- **WP0** Planning for all WPs, as well as specific initial tasks within WPs, delivered in the Inception Report
- **WP1** Analysis and mapping of industrial actors in FCH supply chains – identifying, mapping and describing the European FCH supply chains for selected applications and their critical components, conducting SWOT and gap analysis compared with other leading world regions. This WP includes scoping the supply chains for this and future WPs, and designing and populating a database of European actors.
- **WP2** Analysis and mapping of knowledge based actors in FCH - identifying, mapping and describing the European knowledge based actors in the same supply chains and components.
- **WP3** Global and EU market scenarios to 2024 and 2030 – developing deployment scenarios for each application globally and regionally, and multiplying these by costs to give market turnover by application and component.
- **WP4** Value chain and manufacturing competitiveness analysis – consideration of value chains and European competitiveness, to identify areas of opportunity at application and component level, to establish where there are opportunities for Europe, and what barriers exist to achieving them
- **WP5** Scenarios for the future of the European FCH value chain - combining European competitiveness and opportunities from WP4 with market turnover from WP3 to give scenarios for the future of the European FCH sector

- **WP6** Recommendations for specific actions and investments – provision of a set of actions to enable opportunities to be exploited in components, applications, and the European FCH sector as a whole

This report lays out the approach and outputs for each stage of the analysis, with some of the detail included as appendices.

1.5 Scope

The scope of applications included within this study was discussed and agreed with FCH JU, based on factors such as:

- Potential to enable significant greenhouse gas (GHG) savings, for example through significant production or use of low GHG hydrogen
- Potential to have material global market size, and potential for large EU share of this market
- The need to limit the scope of the project to a manageable workload, maintaining a meaningful level of detail across applications included

Table 1 below shows the applications assessed, with comments added where applications are not included, or to clarify the scope of the application considered.

Table 1: Application scoping

Application	Inclusion	Comments
TRANSPORT APPLICATIONS		
FCEV (fuel cell electric vehicles i.e. cars)	Yes	
FC (Fuel cell) buses	Yes	
HRS (Hydrogen refuelling stations)	Yes	Note that this includes small compressors and small stationary storage
FC Forklifts	Yes	
Maritime and inland boats	Yes	
HGVs (heavy goods vehicle propulsion)	Yes	
Trains and light rail	Yes	
UAVs (unmanned aerial vehicles)	No	Very small market and GHG savings
STATIONARY APPLICATIONS AND HYDROGEN SUPPLY		
Micro-CHP (combined heat and power)	Yes	0 to 5 kW output
Commercial FC CHP	Yes	5 to <100 kW output
Larger FC CHP & primary power	Yes	100kW – multi MW output scale
Fuel cell APUs (auxiliary power units) for trucks	No	Small near-term market, limited GHG benefit
Electrolysers	Yes	
Hydrogen storage	Yes	Focus on compressed hydrogen
Compressors	No	Small compressors are covered within HRS. Large compressors are supplied by existing mature supply chains and so are not a significant new industry
FC Back-up power systems and FC power generators (gensets)	Yes	These categories were combined as they use similar technologies and systems
Fuel processors / reformers	Yes	Although methane reforming is not generally low GHG, this could be interesting for HRS applications onsite, and biogas applications
APUs for boats and recreational vehicles	No	Very small market and GHG savings
Selected hydrogen storage and transportation options: ammonia and liquid organic hydrogen carriers (LOHC)	Yes	
Use of hydrogen in industry	No	This is not primarily related to the FCH supply chain, but to a wide range of industrial uses, which are too diverse to be included in this study
Gas turbines	No	This is not distinct from the natural gas turbine industry
CROSS CUTTING TECHNOLOGIES		
Test benches and test equipment		Important supporting capabilities for supply chains, discussed at high level only in Appendix A.
Dedicated manufacturing equipment		

This initial list of applications was further scoped down within the project. In some cases, **WP3** showed that an application has a small global market size and value, meaning the EU share of this market will inherently be small, and these applications have been scoped out. In other instances, applications with similar upstream value chains have been grouped together in **WP5.**

The **scope of countries** included is defined as the EU plus Horizon 2020 associated countries[4]. For brevity, the term 'EU', 'Europe' and 'European' is used to represent these countries in this report.

1.6 Organising principles

This report is organised as follows:

Section 1: Introduction

Section 2: Methodology

Section 3: Industry overview

Section 4: Criticality assessment and component cost basis

Section 5: Mapping of supply chains by application

Section 6: Mapping of supply chains by technology

Section 7: Critical components

Section 8: Value chain analysis

Some of the *applications* described in Section 5 include more than one chemistry (e.g., both PEMFC and SOFC micro-CHP systems are being deployed). *Components and supply chains*, however, are strongly dependent on the specific chemistry (both the bill of materials and the supply chains for PEMFC and SOFC micro-CHP systems are largely distinct). Therefore, the application descriptions in Section 5 include some sub-sections covering more than one electro-chemistry. The component-level descriptions in Section 6, however, are organised by the supply chain (i.e. by electro-chemistry). These two frameworks – applications and supply chains – overlap, and some information is inevitably duplicated.

[4] As of 01 January 2017, the following countries are associated to Horizon 2020: Iceland, Norway, Albania, Bosnia and Herzegovina, the former Yugoslav Republic of Macedonia, Montenegro, Serbia, Turkey, Israel, Moldova, Switzerland, Faroe Islands, Ukraine, Tunisia, Georgia, Armenia

2 Methodology

This chapter describes in more detail the methodology used to generate, collate and interpret the information presented in subsequent sections.

2.1 Introduction

A supply chain is typically seen as the physical flow of raw materials and components from suppliers, through manufacturing, to finished goods delivered to customers. The analysis here is based on this definition, for a selection of applications.

Each application has been characterised as follows, to help to show both the absolute status of the supply chains, and how they compare to other regions:

1. Supply chain structure, from specialised material to final product;
2. Selection of all critical components, and then those selected for analysis in more depth;
3. Supply chain diagram listing European actors in selected critical components, with supply chain description
4. Capabilities in and prospects for the applications and critical components in other leading regions of the world, including an overview of companies and knowledge-based actors
5. SWOT analysis of the European supply chain for each application and critical component and a discussion of gaps

These steps allow the strengths and weaknesses of each supply chain to be identified and compared, as described in the following sections.

2.2 Supply chain diagrams and descriptions

Categorising fuel cell supply chains across different chemistries and applications is complex, and some simplification has been adopted for this analysis. This is described below within the more general explanation of the approach.

Scope and boundaries of diagrams

The supply chain diagrams represent the chain from specialised materials (right hand end of diagram) to final application integration (left hand end). They include the components that are physically incorporated in the products used, and those that are specific to FCH supply chains. For example:

- Usually a large number of suppliers can provide standard raw materials, with no skills that are specific to the FCH sector. As a result, only specialised materials for FCH have been included this analysis.
- 'Related' technologies, such as the grid connection for electrolysers and CHP systems, are not included.

The supply chain diagrams are in some cases slightly simplified or aggregated compared with a 'true' supply chain for a given product. This simplification is necessary for two reasons. (i) The supply chains or processes for individual companies often differ, though the final assembly contains broadly the same components. For example, stamping of bipolar plate material may happen before or after coating, or certain components (e.g. humidifiers) may not be used in certain fuel cell system designs. (ii) In ensuring the database structure was not too unwieldy, some compromises on terminology were made.

Where relevant, the supply chain diagrams for different applications have been merged. This is because some components are either identical or extremely similar. For example, a fuel cell membrane for a car is either identical or very similar to one for a bus, and the suppliers are also the same.

Identification of leading suppliers

A selection of leading European suppliers[5] for each selected critical component are given for each supply chain, based on those who completed the database questionnaire, and further E4tech research. Note that the supplier lists in the database are not comprehensive; the database responses were not exhaustive and very significant ongoing work would be required to maintain and grow actor lists. There are almost certainly omissions amongst European actors, and some countries are more completely represented than others, but the database is large and we believe it captures the majority of actors, and certainly enough to support the analysis and conclusions of this study.

Identification of knowledge based actors

Information on knowledge based actors (KBAs) including university groups and research institutes has been gathered through the database entries and through desk research. Europe has many strong KBAs, including some that are world-leading, and they provide essential support for the FCH sector, both addressing specifically directed research questions and proactively identifying new directions. By their nature, however, they are hard to link to a specific application. They typically act upstream in the supply chain in areas that can affect many different applications (e.g. fundamental catalysis) or at a more applied level which can still be relevant generically (e.g. integrated system modelling for optimising thermal management).

KBAs are included in the database and a selection of relevant actors is discussed within specific application and technology areas.

Definition of 'European' companies and 'suppliers'

A clear definition of 'European' companies is hard to establish. Most of those included in this analysis are those with headquarters in Europe, as in practice many global companies will have European manufacturing locations. In some cases a European company has been acquired by an overseas company but the European presence is still substantial (e.g. Hydrogenics' electrolyser plant, Dantherm's purchase by Ballard, Greenerity's purchase by Toray) and these are also included. Here, 'suppliers' are considered to be those organisations that will sell the particular component they produce to others. It does not include those who manufacture it internally and do not offer it for sale.

The number of suppliers listed gives an initial indication of the level of strength in a given area of the supply chain, though it also needs to be considered alongside an indication of the strength of the company. If several companies can supply a component, but all are small and have limited resources, this still leaves the supply chain at risk. Likewise, having only one very strong supplier is a concern, as it means that competition is limited, and that the market is critically dependent on a single source.

[5] While care has been taken to refer to as many sources as possible, including actors who completed the database questionnaire, some actors may have been inadvertently included or excluded.

Supply chain description

For each application we have included a discussion of:

- the system integration actors shown on the graphic
- the commonality of components within applications and supply chains, including aspects such as how far upstream in the supply chain the convergence takes place, e.g., within PEM, the platinum (far upstream) is agnostic to application, while the MEA is only partially agnostic. At the downstream end, applications are each unique.
- where available the typical relationships between companies within the supply chain for the application, highlighting whether these relationships vary in Europe compared with the rest of the world, or whether they vary by technology. For example, this considers whether integrators source components from a wide range of suppliers, tend to manufacture key components in house, or rely on just a very few specialised external suppliers.
- an indication of knowledge based capabilities at application and critical component level, including specialist skill sets.

Supply chain relationships

It is very important to clarify that this report is not designed to identify the specific existing supply chain for any component or application. While the companies in the different boxes *could* supply those downstream of them, many such relationships are confidential and real existing supply chains for any product or application should not be reconstructed by picking one company from each of the boxes. In other words, each box is entirely independent for the purposes of this study. For example, while a stack supplier *could in principle* source their bipolar plate, membrane electrode assembly (MEA) and gas diffusion layer (GDL) from companies in the box immediately to the right, they could also have used other suppliers, including from outside Europe. Equally, a given system supplier may not source stacks at all, but source components and manufacture stacks in-house, so some steps in the chain will not exist for some actors. Specific supply relationships can only be mentioned when they are fully public.

In addition, most companies will prefer to have more than one supplier for most components, to reduce risk. A systemic weakness for fuel cell and hydrogen supply chains today is that such dual-sourcing can be hard to achieve. Components made by different companies are fully substitutable in only a few cases, and in some cases component choice is extremely limited as very few companies supply each part.

Because of the nascent status of the technology and the supply chain, significant disparities can exist between the best established and most solid supply chain players (typically large corporations with a strategic investment in the FCH area) and the smaller, typically pure-play early-stage companies. The latter have often historically had very good technology, but lacked the resources to take it to market, or to develop the procedures required for high quality, high throughput manufacturing. It is likely that this will remain the case, and so these pure-play companies will often either remain in smaller markets or possibly be merged into other entities. The names on any future supply chain diagram are therefore likely to be different, with some companies dropping out of certain applications, and some disappearing.

Inevitably, only limited information can be shown on the supply chain diagrams without rendering them too difficult to interpret. For example, relationships between companies and other entities (e.g. knowledge-based actors) can be very important and affect component choices and supplier locations, amongst other things. In Europe such relationships vary widely. Some companies prefer to have strong and close relationships with a few partners and will source components by preference from them, even at a possible (small) cost disadvantage. Others are driven only by cost and quality and will change suppliers relatively frequently. These subtleties cannot easily be noted on the diagrams.

Structures and relationships also vary by type of supply chain. Consistency is valued in automotive supply chains in particular, as components have to meet very rigorous standards and be delivered exactly on time. Relationships are developed over years. This means that entering the supply chain is hard, especially for a new or small entity like a pure-play fuel cell stack developer. The fact that Europe has independent stack suppliers at the current stage of supply chain evolution unfortunately does not guarantee that these suppliers will remain in business as the industry grows – although their technology may be acquired by a larger company and continue to be used.

In general, consumer-facing industries with high levels of mass-production and low margins have very strict supply criteria and are hard for small companies to serve. In contrast, so-called niche markets offer more opportunity for such companies to remain engaged.

The picture in parts of Asia, particularly Japan and Korea, is dominated by large corporations. Many supply relationships are essentially internal – for example between companies in the same group (e.g. Toyota sourcing from Toyota Industries). This is much less common in Europe and North America where the trend has been to break up such conglomerates (e.g. Delphi splitting out from Ford).

2.3 Supporting database, questionnaire and survey

The actor information in this report was based initially on existing knowledge and supplemented by a significant data gathering effort. An online questionnaire was used to collect information on the FCH activities of European industrial and knowledge-based actors (KBAs), to complement the data collated in the precursor FCHJU Supply Chain study. It was also designed to capture more granular information about activities by application, and included questions for technology users and manufacturers, as well as KBAs such as research organisations, consultancies, industry associations and government agencies. Technologies covered were fuel cells, electrolysers, hydrogen storage and transport, hydrogen refuelling stations and fuel processors. In addition, a survey was conducted that asked actors to provide information on their views on the European competitiveness in the FCH applications that they are engaged with. The questionnaire and survey could both be accessed from the FCHJU's projects webpage in March and April 2018. Findings from the questionnaire and survey informed the analysis in subsequent sections of this report. The database of actors will be used internally by the FCHJU.

2.4 Cost inputs

An important part of the value chain analysis is related to cost. Costs within most FCH technologies remain uncertain and are evolving rapidly. They differ between suppliers, applications and technologies and are often highly confidential. Cost studies published in the open literature were therefore used as inputs to the analysis, to identify both critical components and opportunities for Europe of suitable value for further consideration. Because the range of applications and technologies considered is very wide, and both supply chain and technologies are evolving, the costs reported here will not be true costs for any component or application. However, they are considered suitably representative for the tasks above.

Two categories of cost analysis exist in the open literature, one based on manufacturing cost and another based on price. Manufacturing cost analyses tend to be 'bottom-up' studies that estimate the cost to a manufacturer as a function of fixed (e.g. facilities and equipment) and variable (e.g. labour and materials) costs. These have the advantage of providing detailed insight into what factors most affect a device's cost, whether it is individual components, certain materials, equipment cost, production speed, etc. However, bottom-up cost models can suffer from projecting over-optimistic costs (i.e. too low) and are difficult to validate since most manufacturers consider details of their cost structures sensitive or proprietary. Top-down models, based on supplier quotes or aggregate quotes, typically report a sales price that the customer pays and have precisely the opposite strengths and weaknesses. They can be fairly reliable estimates of the actual price paid, but provide little insight into what goes into that price or where there are opportunities for reductions.

Cost studies exist for most applications considered here, but some specific details – such as power level – or precise usage – such as heavy goods vehicles (HGVs) – have not been individually analysed. In these cases, the best available study with greatest overlap was used as the cost basis. For example, fuel cell electric buses (FCEBs) have been studied in detail using a bottom-up manufacturing cost approach, so this was used to assess HGV costs. This is defensible at this stage of sector development, since evidence from demonstration programmes and from systems performance analysis studies suggests that a modular approach to fuel cell stack design which covers the majority of transportation applications is emerging, even though the industry structures are different and so final assembly will be approached differently. Moreover, it is reasonable to assume that systems will be hybridized to take advantage of the best performance characteristics of the fuel cell and battery.

Learning rate curves for component cost were developed for each critical component, using the cost studies for validation points at production volumes relevant to the deployment scenarios. Labour, materials, and capex splits were assigned consistent with high rate production, where capex utilisation is highest. Balance of system components that were not selected in the critical components evaluation, were modelled using a curve for their aggregate cost, so that the sum of the critical components and balance of system reflected the system cost as accurately as possible. Throughout this study, analyses based on the reported cost breakdowns are assumed to be in 2018 Euros.

2.5 Methodology for 'critical' component selection

All applications contain a very large number of components, some of which are not unique to FCH, and some of which are already manufactured in large quantities. To identify the most important areas in FCH for Europe, and to render the analysis manageable, it was constrained in several dimensions. Applications with small markets were not analysed in detail; European supply chain strength was considered, and only a subset of components was analysed in depth. A short list of 'critical' components was drawn up using a scoring approach described below, and then only a subset of selected components within that short list was analysed in detail.

All components are of course vital to the final application, and so this exercise should *not* be considered as a ranking of where research funding or other support should be allocated. However, the focus has the benefits of allowing meaningful depth of analysis for the selected components, and of simplifying communication. A structured quantitative methodology was used to identify these components, based on six characteristics, each ranked 1 (critical) or 0 (not critical). As this analysis considers value add for Europe, and not only technical performance, socioeconomic and market considerations were included. Weighting was not used, as it was felt to add complexity and subjectivity to what is already a partially subjective assessment.

It is of course impossible to find a perfect definition of 'criticality', or a score that all stakeholders will agree with. However, the selected components are considered representative and suitable for this analysis, in that they span a range of technology areas and supply chain positions and offer transferable insights into the wider potential for the sector.

- **Performance** – system performance is significantly affected by component or sub-system performance.
- **Cost** – the component or sub-system represents a significant fraction of the system cost.
- **Technical Evolution** – the component or sub-system is undergoing or is expected to undergo technological evolution that will lead to significant cost reduction or system performance improvement in the near-term.
- **Supplier Base** – there is a limited supplier base of appropriate quality or the supply base is controlled or concentrated in one global region.
- **New Market** – growth of the fuel cell and hydrogen market would result in a unique new market for the component or sub-system.
- **Socioeconomic Impact** – the component or sub-system represents a unique area of job growth.

For each application, a representative system and list of components was defined. The components were then tested against the six critical characteristics above, informed by cost analysis literature, the team's collected knowledge and data sets, and external experts as needed.

A binary score of 1 (meets the definition) or 0 (does not meet the definition) is assigned to each of the characteristics. The cut-off cumulative score for criticality was set at 4, i.e. a component that meets **a majority** of the above criteria. This approach produced a subset of critical components, which would generally be intuitively familiar to an expert in the field, and a comprehensive list of critical components is given in Table 5 to Table 16.

An illustrative example is shown in Table 2 for a component that **meets** all six criticality characteristics, and hence scores 6 points in the assessment: Catalyst in automotive PEM fuel cells. Components that scored 4 and more were categorised as critical components, but not analysed in more detail (see example in Table 3, DC-to-AC inverters).

The critical components actually included in the analysis were then selected from the main set. The majority of these 'selected critical components' score 6, i.e. they meet all of the assessment criteria. In a few cases they have been promoted to help inform the analysis, for example where there is a clear economic interest in Europe. It became clear after completing the assessment that in some cases a feature of criticality was excluded through this choice of factors, or certain characteristics had a greater weight than the binary scoring method allowed. For example, while pressure vessels scored lower than some components, they were selected as critical components given their importance in enabling the spread of multiple applications.

Further detail is included in Section 7, where the selected components are discussed per technology and more analysis is presented.

Table 2: Automotive catalyst criticality evaluation

Criteria	Score	Rationale
Performance	1	Platinum-based catalysts bear primary responsibility for converting hydrogen chemical energy into electrical power; consequently, the fuel cell power plant size, cost, and durability are all directly linked to the catalyst.
Cost	1	Due to high platinum material costs, PEMFC cost is sensitive to the amount of catalyst required[6].
Technical evolution	1	About 50% of the U.S. Department of Energy Fuel Cell Program budget is spent on catalyst development. Due in part to these investments, projected fuel cell system costs have decreased by nearly half[7].
Supplier base	1	Due to the cost and complexity of handling precious metals and the technical complexity of fuel cell catalyst manufacture, only a small number of suppliers have the capability to supply catalyst for high volume automotive production.
New market	1	Catalyst is a unique component specially designed for PEMFCs and is not shared with other technologies. Thus, catalysts would represent a new market opportunity.
Socioeconomic Impact	1	Catalyst production is technically complex and is expected to provide a range of jobs.

Table 3: Automotive power electronics / inverters criticality evaluation.

Criteria	Score	Rationale
Performance	0	Stack cost and performance is independent of inverter performance.
Cost	1	Inverter cost can be nearly twice the fuel cell system cost[8].
Technical evolution	1	Research into wide bandgap semiconductors has the potential to significantly improve inverter efficiency.
Supplier base	0	The technology is mature and has a competitive supply base
New market	1	DC-to-AC inverters are common to all electric vehicles.
Socioeconomic Impact	1	Impact is not known from cost models, but we anticipate that the impact would be similar to other semiconductor industries. Thus, growth in electric vehicle markets is expected to result in highly skilled jobs to support demand for power electronics.

[6] Brian D. James et al., 2017, "Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2016 Update" https://energy.gov/sites/prod/files/2017/06/f34/fcto_sa_2016_pemfc_transportation_cost_analysis.pdf
[7] Dimitrios Papageorgopoulos, 2017, "Fuel Cells R&D Overview" https://www.hydrogen.energy.gov/pdfs/review18/fc01_papageorgopoulos_2018_o.pdf
[8] Battelle, 2016, "Manufacturing Cost Analysis of 1, 5, 10 and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and
A 'Technology Readiness Level' (TRL) and a Manufacturing Readiness Level (MRL) could in principle be assigned to the key components discussed. These levels represent the status of maturity of a component or system, as defined by NASA and the US Department of Energy, amongst others[8].
Power Applications", https://energy.gov/sites/prod/files/2016/07/f33/fcto_battelle_mfg_cost_analysis_pp_chp_fc_systems.pdf

3 Industry overview

3.1 Europe

3.1.1 Industrial actors

An overview of the industrial FCH actors in Europe is given in the separate Findings report.

3.1.2 Knowledge and research based actors (KBAs)

The work of hundreds of KBAs in Europe is relevant to the extensive space covered by FCH technologies. 238 KBAs (Research and Higher Education organisations) have participated in FCHJU projects alone, within the Framework Seven (FP7) and Horizon 2020 (H2020) programmes[9], across 219 projects. These KBAs also conduct relevant R&D in FCH outside FCHJU-funded projects, using third party funding or parts of their base funding as public research organisations. The total activity (research funding and headcount) of European KBAs linked to FCH is not documented in the public domain and very limited data were gathered through the questionnaire process in this study. While significant additional effort has been made to research and add further organisations, the numbers represented are very likely to be lower than the actual KBAs who can and do contribute to the sector. Categorisation is also somewhat complex, as for much fundamental research (e.g. catalyst structures or ceramic materials) the work may or may not be applicable to FCH, and then it may or may not carry across different areas within FCH (stationary, transport, high- or low-temperature, etc).

The actors who have participated in FCHJU-related projects give some indication of European capabilities. Figure 2 shows the number of KBAs that are involved in FCHJU H2020 and FP7 projects, split by the type of high-level research area, also known as the pillar. Energy includes the production and storage of hydrogen, as well as the use of fuel cells in stationary, APU and portable applications. Cross-cutting refers to projects that span the FCH industry, working on horizontal aspects such as pre-normative research (PNR), education, sustainability and safety, as some examples. The transport category focusses on fuel cell applications for transport. Throughout this analysis, the number of unique KBAs in a category has been calculated per category, and therefore these numbers are not additive and the sum of constituent categories does not equal the total unique KBAs across all H2020 and FP7 projects. This is because some KBAs participated in projects across various focus areas, as well as across various applications.

[9] The last H2020 call that is included in the data is H2020-JTI-FCH-2017-1.

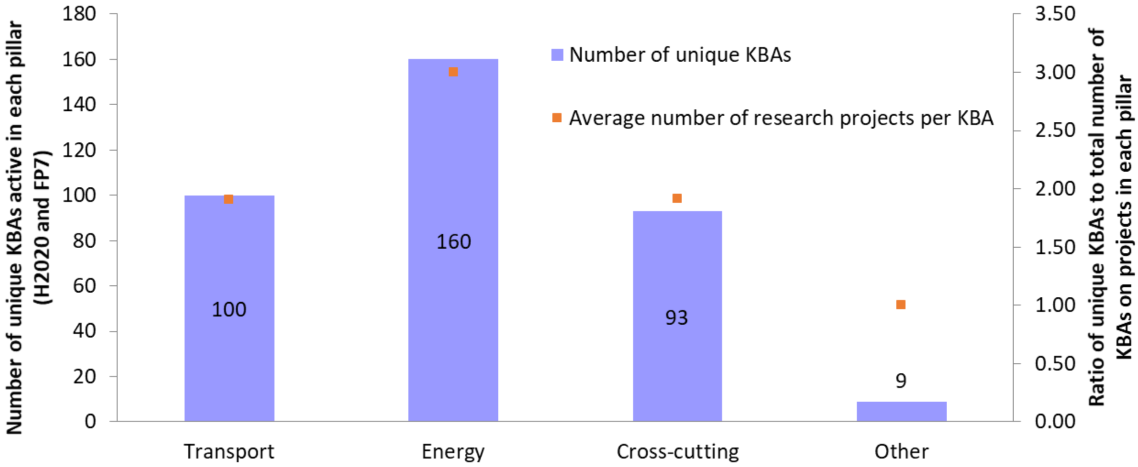

Figure 2: KBAs in research pillars from H2020 and FP7 projects awarded by FCHJU

Figure 2 also gives a ratio for each category, showing on average the number of projects per unique KBA. This gives an indication on the spread of research across different institutions. However, it is also influenced by differentiation within high-level categorisations. For example, the energy pillar is likely to have actors that have skills applicable to many more specific fields, meaning one KBA may be part of more projects within the high-level category. Figure 2 shows that there are the most KBAs in the energy pillar, unsurprising considering the mix of fuel cell, storage, distribution and hydrogen production applications (See Figure 4 for more detail), whereas the number of KBAs in transport and cross-cutting are similar. KBAs in the energy pillar average ~3 projects per KBA, with KBAs in transport and cross-cutting pillars averaging approximately 1 less project per KBA, with a value of ~2.

Figure 3 shows the application breakdown of the transport pillar and that research in general stacks and systems for transport applications has the most KBAs, with less KBAs specialising in the individual applications. All the specific transport applications average ~1 project per KBA, with KBAs working on general transport system averaging just below 2. Figure 3 also shows that the number of KBAs and number of projects in the specific transport applications is fairly even apart from for trucks, which has one KBA in one project. Once again, the sum of the values in Figure 3 is not representative of unique KBAs in transport, as some worked on multiple projects across different focus areas and technologies.

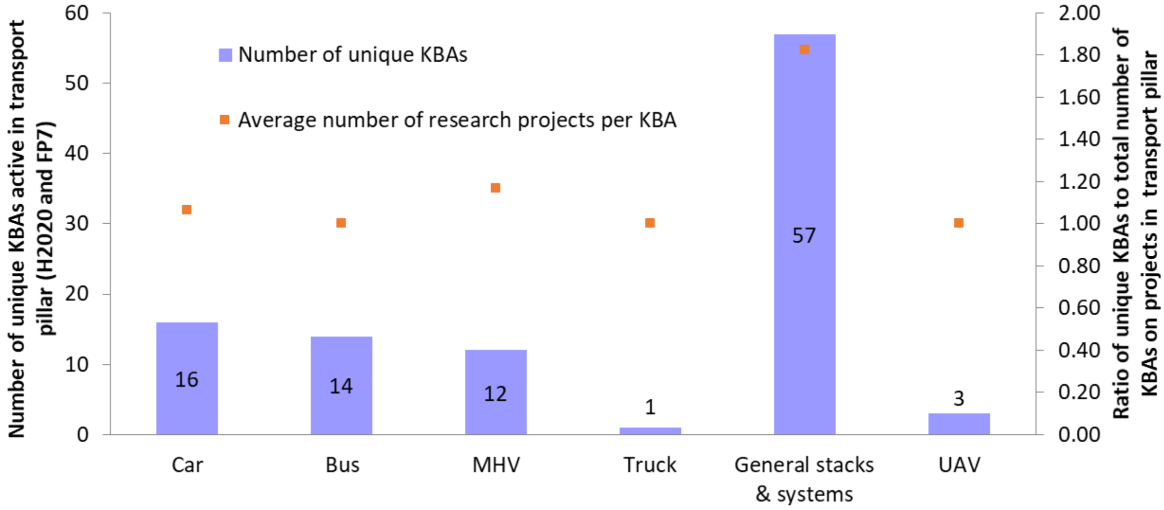

Figure 3: KBAs in specific applications of transport pillar from H2020 and FP7 projects awarded by FCHJU

The application breakdown of the energy pillar is shown in Figure 4, with the most KBAs working on stationary fuel cell and hydrogen production projects. KBAs in stationary fuel cell applications are on average working just over 2.5 projects; slightly more projects on average than in the transport pillar (see Figure 2). The research into hydrogen production is split between electrolysers and other, where other covers other production processes e.g photo-electrochemistry and other processes involved in production, such as reforming and purification. There are not as many KBAs working in storage and hydrogen refuelling stations but this may also be a product of there being fewer FCHJU projects in this area.

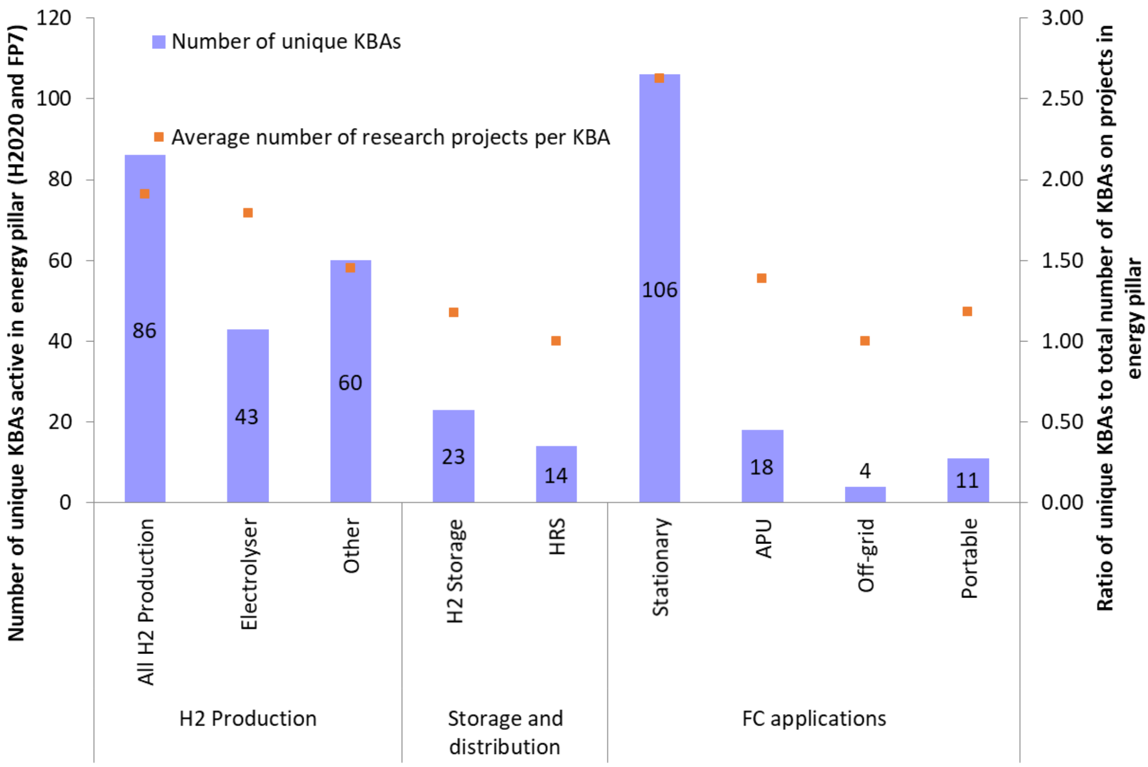

Figure 4: KBAs in specific applications of energy pillar from H2020 and FP7 projects awarded by FCHJU

Figure 5 shows the breakdown of the cross-cutting pillar. The areas with the most active KBAs are education, social acceptance and safety. This may reflect the barriers seen by the FCH industry to wide-scale deployment. Hydrogen safety is an important area of research, due to it being a low-flash point fuel. However, a common misconception is that hydrogen is significantly more dangerous and explosive than fuels used today, requiring social acceptance and education to prepare for wide-scale use. The number of KBAs in other areas is balanced, ranging between 17 and 10. Cross-cutting work on stack technology is also include in this list.

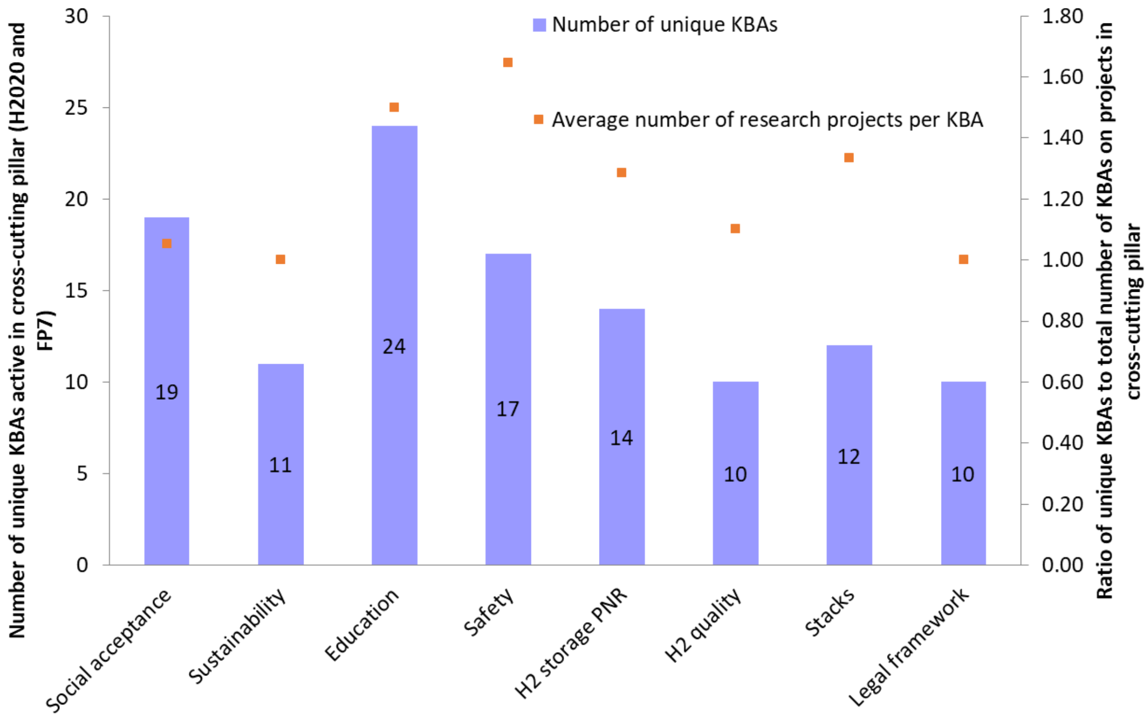

Figure 5: KBAs in specific applications of cross-cutting pillar from H2020 and FP7 projects awarded by FCHJU

The KBAs were also looked at by technology, as we well as application, and this is shown in Figure 6. In fuel cells, PEMFC has the most unique KBAs working on the technology, mainly due to it being the only technology considered for use within transport. SOFC has approximately half the number of unique KBAs when compared to PEMFC, with the highest average number of projects per KBA across all the technologies. Other FC technologies have low levels of projects and associated KBAs. There are a relatively even number of KBAs in each of the electrolyser technologies, when compared to FC technologies. However, the largest number of KBA is involved in solid-oxide electrolyser projects.

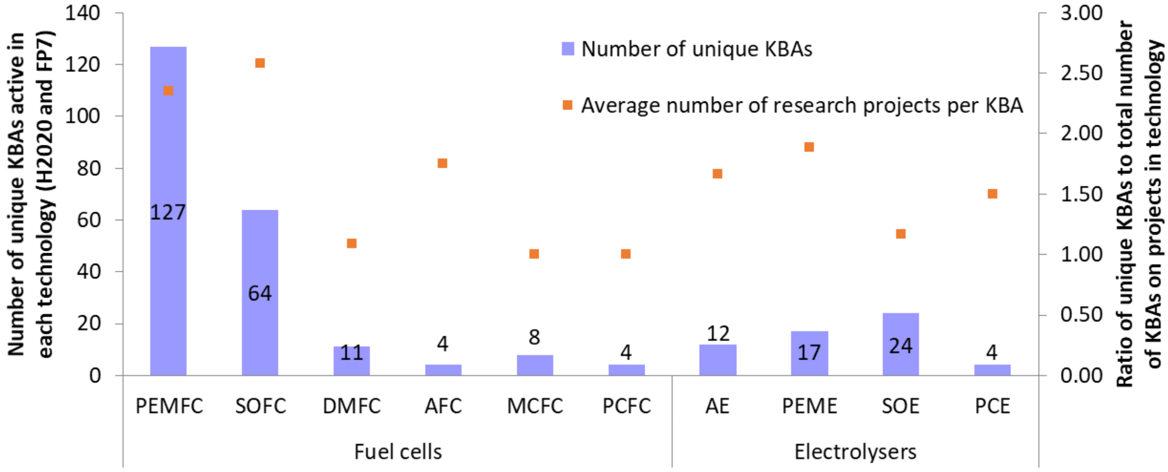

Figure 6: KBAs in each technology category from H2020 and FP7 projects awarded by FCHJU

A like-for-like comparison of European KBAs with other world regions is extremely hard to undertake. Like the European KBAs, the global ones are not fully categorised, and world-class actors exist in most regions in most disciplines. Nevertheless, experience and expert discussion suggest that Europe ranks well globally across the vast majority of areas, from fundamental R&D to systems design and applied engineering. The standard of publications is high, and a significant amount of directly-commissioned work is said to come from non-European organisations. The other established world regions (Japan, the US, Canada and increasingly Korea) also rank well however, meaning that Europe is competitive, but not dominant. China is making rapid progress, and has strong fundamental science in particular, but much of the more applied research lags behind the regions mentioned above.

3.2 Other leading world regions

Europe has world-leading companies and research capabilities in many FCH technologies and applications, and works closely with industry and researchers globally. Its strengths and weaknesses can be considered both in absolute and relative terms, compared to other leading regions.

This section provides brief profiles of leading non-European regions, touching on global players, applications and critical components to provide a basis for the SWOT and gap analysis. For knowledge based actors, it includes some of the most important geographical centres of excellence. This is based on the project team's existing knowledge, on desk research, and on discussions with academic and industry experts. The analysis is not intended to be exhaustive, so the information provided here aims to focus on the main topics and information of relevance.

3.2.1 Japan

Japan is very strong in most areas in FCH, from fundamental science to applications and manufacturing. It has expertise in every fuel cell chemistry, although arguably has only recently caught up (and perhaps overtaken) Europe on SOFC industrialisation. Japan is the strongest region globally in terms of plans and linkages between government, research and industry actors, who all meet and discuss these frequently. Japanese technology is also typically strong, often developed incrementally, through multiple iterations, rather than breakthroughs. Many major corporations in Japan have hydrogen and/or fuel cell technology programmes, and others have increasing interests in business models and technology exploitation.

The Japanese fuel cell industry is given strong direction and financial support through national government policy, with hydrogen embedded into the national energy strategy and supported through three key phases: roll-out of fuel cells (and cost reduction); hydrogen mass production (and cost reduction); and making the hydrogen used 'CO_2 free' (green hydrogen). Much of this is overseen by the Ministry of Economy, Trade and Industry (METI), and research support comes mainly from the government agency New Energy and Industrial Technology Development Organisation (NEDO), funding R&D to the amount of $100m USD in FY 2018. Current Japanese projects include the import of significant amounts of hydrogen in 2020 from abroad, via liquefied hydrogen made from brown coal in Victoria, Australia and via a chemical carrier using hydrogen from renewable sources in Brunei[10].

Stationary fuel cells

In stationary fuel cells Japan has world-leading technology in sub-kW CHP units, with a total of over 250,000 installed and operating by early 2018. The sector was stimulated by the ene.farm programme, a subsidy scheme for market uptake of mCHP units to drive down the cost. The majority are PEM units from Panasonic and Toshiba, though Toshiba is no longer manufacturing and an increasing proportion of installations are from Aisin Seiki using Kyocera SOFC technology. Small-scale reformers are produced by both Tokyo Gas and Osaka Gas and are some of the best worldwide. Toto and NGK are developing SOFC units, while Mitsubishi-Hitachi Power Systems has operating installations of its 250kW SOFC-gas turbine hybrid system, and is moving to 1MW systems. Toyota Tsusho has distribution agreement with Ballard Power Systems to sell their fuel cells in Japan[11].

Fuji Electric primarily develops PAFC systems which it sells commercially. Doosan in Korea is the only other company producing PAFC. Fuji Electric is also developing SOFC capabilities with the aim to create power generation and cogeneration systems that provide power on the 10-100kW scale[12].

Other companies have varying levels of activity, for example Magnex, a specialist in magnetic systems for computing, has also developed supply capability for a range of SOFC components and subassemblies.

FCEV

The Japanese government is targeting local deployment of 40,000 FCEVs by 2020, though in October 2017 there were only 2,161 in Japan[13]. Nevertheless, Japanese automakers are amongst those setting the pace globally for development for FCEV technology and commercialisation. Toyota's Mirai FCEV was launched in Japan in 2014 and uses Toyota's own PEM fuel cell stack technology and its own 70MPa high pressure hydrogen tanks. Honda's Clarity FCEV, launched in Japan in 2016, again uses an in-house PEM stack. Nissan has developed its own PEM stack and system technology, which has been implemented in prototype Nissan vehicles but currently has no commercial offering. It does however have an SOFC vehicle system that uses bio-ethanol as fuel source, the stack is based on Ceres Power technology[14]. A very novel '2D manufacturing

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[10] Reuters (2017) 'Norway races Australia to fulfill Japan's hydrogen society dream' Available at: https://www.reuters.com/article/us-japan-hydrogen-race/norway-races-australia-to-fulfill-japans-hydrogen-society-dream-idUSKBN17U1QA
[11] Toyota Tsusho (2018) 'Toyota Tsusho to Supply Fuel Cells for Use as Emergency Power Supply'. Available at: http://www.toyota-tsusho.com/english/press/detail/180405_004158.html
[12] Fuji Electric (Accessed April 2018) 'Solid Oxide Fuel Cell Power Generation Systems (SOFC)'. Available at: https://www.fujielectric.com/company/research_development/theme/fuelcell.html
[13] International Partnership for Hydrogen and Fuel Cells in the Economy (2017) 'IPHE Country Update November 2017'. Available at: https://docs.wixstatic.com/ugd/45185a_5f6d4c8dc906443cae4474c6b1d3002d.pdf
[14] Fleet News (2016) 'Nissan signs deal with Ceres Power for alternative fuel cell' Available at: https://www.fleetnews.co.uk/news/manufacturer-news/2016/07/15/nissan-signs-deal-with-ceres-power-for-alternative-fuel-cell

process' is also in development for reducing manufacturing costs[15]. Suzuki has worked mainly in two-wheelers, partnering with the UK's Intelligent Energy for their fuel cell stack and system technology[16]. For LCVs, Toyota is working with 7-11, amongst others, to develop FC delivery trucks.

FCEB

Japan has a target of 100 FCEBs in Tokyo alone in 2020, for the Olympics, supported by subsidies for R&D and demonstration projects[17]. Toyota and subsidiary Hino Motors have collaborated to produce a FCEB using the Hino bus and Toyota Mirai FC technology[18,19].

HRS

Japanese government targets for HRS deployment are supported by subsidies for the capital costs and operational costs of the HRS. Japan aims to build both 700 and 350 bar HRSs, and 11 large players are working together to expand Japanese refuelling capabilities[20]. These players are Toyota, Honda, Nissan, Iwatani, JX Nippon Oil & Energy Corporation, Toyota Tsusho, Idemitsu Kosan, Tokyo Gas, Toho Gas, Air Liquide and the Development Bank of Japan. Deployment of HRSs has been slower than hoped because Japan's very strict safety regulations greatly increase the cost of a fuelling station compared to other regions, and make permitting difficult.

FC forklifts

Toyota has integrated its own fuel cell system into some of its forklifts. 20 are currently in demonstration at Toyota manufacturing sites, but are not yet a commercial offering, though Toyota will continue to replace its own forklift fleet with fuel cell forklifts[21].

Maritime and inland boats

Relatively little work is being conducted in Japan on boat applications. Yanmar, the National Maritime Research Institute (NMRI) and the Japan Ship Technology Research Association (JSTRA) are running a test project on a 16.5m boat, using Ballard fuel cells supplied to Yanmar by Toyota Tsusho[22]. This project is also aiming to help the development of safety guidelines for hydrogen fuel cell vessels under 20 tonnes, operating in Japanese waters.

HGVs

There are no specific targets for HGV deployment within Japan. Toyota has trialled its Mirai technology in an 'Alpha' and 'Beta' version of a Class 8 HGV in the US, using a Kenworth vehicle[23], while Hino (a Toyota

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[15] Hasegawa, T. (2016) '2D Parts Revolution – How Electrochemical Power Generation Devices Bring Economic Opportunities' Conference paper. Available at: http://gerpisa.org/node/3425
[16] H2 Today (2016) 'Suzuki to launch a fuel cell motorbike in Japan'. Available at: https://hydrogentoday.info/news/912
[17] International Partnership for Hydrogen and Fuel Cells in the Economy (2017) 'IPHE Country Update November 2017'. Available at: https://docs.wixstatic.com/ugd/45185a_5f6d4c8dc906443cae4474c6b1d3002d.pdf
[18] Toyota Global Newsroom (2017) 'Toyota to Start Sales of Fuel Cell Buses under the Toyota Brand from Early 2017'. Available at: https://newsroom.toyota.co.jp/en/detail/13965745
[19] Toyota Global Newsroom (2017) 'Toyota Delivers Fuel Cell Bus to Tokyo Metropolitan Government'. Available at: https://newsroom.toyota.co.jp/en/detail/15160167
[20] InsideEVs (2017) '11 Japanese Powerhouses Go All In For Hydrogen Stations'. Available at: https://insideevs.com/japanese-companies-hydrogen-stations/
[21] Toyota (2018) 'Toyota Accelerates Use of Hydrogen at its Plants' Available at: https://newsroom.toyota.co.jp/en/corporate/21565079.html
[22] Flaherty (2018) 'Japanese project tests out hydrogen fuel cells in boat' EE News. Available at: http://www.eenewspower.com/news/japanese-project-tests-out-hydrogen-fuel-cells-boat
[23] E4tech (2017) 'Fuel Cell Industry Review 2017'. Available at:

subsidiary) has recently released a conventional Class 8 sized truck for the US market (previously Hino only made smaller trucks)[24]. This may be with the aim to integrate Toyota FC technology into HGVs and sell into the US market. Toyota are well positioned in this emerging application with relatively few companies having demonstrated FC technology within HGVs.

Train and light rail

Japan began research into fuel cell use in rail applications early on. In 2006, the East Japan Railway Company developed a prototype fuel cell hybrid train, though since then most of the developments have been within Europe and North America. Some prototypes have been demonstrated in Japan, developed by Japan's Railway Technical Institute[25].

Electrolysers

The Japanese water electrolyser industry has been quiet, despite the country's plans to become a hydrogen economy, but is increasingly active. Toshiba has developed an alkaline water electrolyser technology, producing Japan's largest system of this type after the success of a smaller demonstration project. Toshiba has also developed a solid oxide electrolysis cell (SOEC) with the support of NEDO. The potential applications of this technology will be investigated before further development[26,27]. Asahi Kasei produces chlor-alkali electrolysers[28] and is now using the technology as a base for water electrolysis products, but also produces PEM membranes for fuel cell, electrolyser and redox flow battery applications[29]. Other players include Hitachi Zosen – PEM[30]; Kobelco – PEM & alkaline; and Honda, which has a PEM electrolyser-based home refuelling station[31].

Hydrogen storage

Japan has a long history of conventional metal hydride storage and deep research into the fundamentals of solid-state storage more broadly. Examples include Japan Steel Works' commercial hydride cylinders, and Kobe Steel conducting commercial research into lightweight composite materials for FCEVs that will be strong enough to protect hydrogen tanks in case of collisions[32]. Chiyoda has developed a liquid organic hydrogen carrier (methylcyclohexane and toluene) technology, for transportation of hydrogenated material in traditional fuel tanks[33].

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[24] Freightwaves (2018) 'Hino enters Class 8 truck market with XL Series'. Available at: https://www.freightwaves.com/news/equipment/hino-unveils-class8-truck
[25] Hydrogen Fuel News (2017) 'Trains powered by fuel cells now being tested in Japan'. Available at:
[26] FuelCellWorks (2016) 'Toshiba Develops Japan's Largest Alkaline Water Electrolysis Hydrogen Production System'. Available at: https://fuelcellsworks.com/news/toshiba-develops-japans-largest-alkaline-water-electrolysis-hydrogen-production-system
[27] NEDO (2015) 'Hydrogen Production Activities in Japan'. Available at: https://www.sintef.no/contentassets/1ac5d74dbeac4e5ea19aa3079df0997a/01-03_jo_nedo.pdf
[28] Asahi Kasei (Accessed April 2018) 'Electrolyzer Acilyzer'. Available at: http://www.asahi-kasei.co.jp/salt-electrolysis/en/index.html
[29] Asahi Kasei (Accessed April 2018) 'Asahi Kasei Proton Exchange Membrane & Ionomer'. Available at: http://www.asahi-kasei.co.jp/pem/en/index.html
[30] Hitachi Zosen Corporation (2018) 'Hitachi Zosen Delivers Hydrogen Generation System HYDROSPRING'. Available at: http://www.hitachizosen.co.jp/english/release/2018/04/002996.html
[31] US DoE (2016) 'Fuel Cell Technologies Office HydroGEN Consortium Webinar Series, Part 2 of 3: Electrolysis'. Available at: https://www.energy.gov/sites/prod/files/2016/11/f34/fcto_webinarslides_h2awsm_consortia_electrolysis_overview_111516_0.pdf
[32] "Kobe Steel working on materials for fuel cell cars", Nikkei Asian Review, September 11, 2014. Available at: https://asia.nikkei.com/Business/Companies/Kobe-Steel-working-on-materials-for-fuel-cell-cars
[33] Chiyoda Corporation (Accessed April 2018) 'What is "SPERA HYDROGEN" system'. Available at: https://www.chiyodacorp.com/en/service/spera-hydrogen/innovations/

Testing

Japan also has some specialised testing facilities:

- Japanese Automotive Research Institute (JARI) has a testing facility for fuel cells and fuel cell vehicles, including crash and fire testing[34].
- Japanese Gas Association (JGA) has a long-term stationary fuel cell testing facility[35].

Components

Toray produce MEAs for PEMFC and carbon fibre for GDL and tanks. It owns Greenerity in Germany. Tanaka produces catalysts for PEMFC (mainly platinum and platinum ruthenium alloy/carbon catalysts[36]) and is one of the top 3 companies in the world for this component along with Johnson Matthey and Umicore. A seven-fold increase in production capacity is scheduled to come online in early 2019[37]. A very wide range of other companies are capable of producing specialised components, such as Nippon Shokubai, which makes SOFC products like electrolytes, and Toyota Industries, which supplies bespoke air handling equipment for Toyota FCEVs.

Knowledge-based actors

Many universities have FCH capability, and a few are global leaders. Japan's national fuel cell and hydrogen research capability overall is world-class. Examples include the National Institute of Advanced Industrial Science and Technology (AIST), a large institute covering excellent fundamentals in all areas of fuel cells. Its Fuel Cell Material Group focuses on materials research for SOFC technology for higher efficiencies, longer-term operation and application of different hydrocarbon fuels[38], while the Advanced Fuel Cell Research Group focuses on Polymer Electrolyte Fuel Cells and concepts such as reversible fuel cells, developing new component materials and technology concepts[39]. FC-Cubic is an association of OEMs and research institutions set up specifically with the goal of advancing PEMFC fuel cell technology, to reduce costs and increase durability and performance.

Kyushu University is strong on the fundamentals of SOFC[40], and hosts the internationally collaborative International Institute for Carbon-Neutral Energy Research (I^2CNER)[41], which includes divisions specialising in hydrogen material compatibility – research into performance and safety of pressurised hydrogen storage vessels; electrochemical energy conversion – R&D into PEMFC and SOFC; Thermal Science and Engineering – improving understanding of thermophysical properties of hydrogen and efficiency of thermal processes; and Catalytic Materials – R&D into novel catalysts. It is even conducting joint research with Yokohama Rubber to develop a low-cost hydrogen refuelling hose and a standard for the quality and characteristics of the hoses.

[34] JARI (2012) 'Introduction to JARI's Test and Research Facilities'. Available at: http://www.jari.or.jp/Portals/0/resource/uploads/AAI_Summit_08-JARI.pdf
[35] Greaves, C., Hart, D. … (2004) 'Fuel cells – the Japanese experience'. Available at: http://www.synnogy.co.uk/publicreports/japan.pdf
[36] Tanaka (Accessed April 2018) 'Platinum and Platinum Ruthenium Alloy/Carbon Catalysts for Polymer Electrolyte Membrane Fuel Cells (PEFCs)'. Available at: http://pro.tanaka.co.jp/en/products/PEFCs.html
[37] Fuelcellsworks (2018) 'TANAKA Expands Fuel Cell Catalyst Production Capacity' https://fuelcellsworks.com/news/tanaka-expands-fuel-cell-catalyst-production-capacity
[38] Fuel Cell Material Group at Energy Technology Research Institute of AIST (Accessed April 2017) 'Research Summary'. Available at: https://unit.aist.go.jp/ieco/fuelcells-mate/research.html
[39] Research Institute of Electrochemical Energy (Accessed April 2018) 'Research outline'. Available at: https://unit.aist.go.jp/riecen/gaf/index_en.html
[40] Kyushu University (Accessed April 2018) 'Research Highlights' Available at: https://www.kyushu-u.ac.jp/en/research/approach/fuel/
[41] I2cner (Accessed May 2018)'Research Divisions' Available at: http://i2cner.kyushu-u.ac.jp/en/team/team_detail.php?code=6

Kyoto University's Department of Energy and Hydrocarbon Chemistry is researching systems and materials related to fuel cell and hydrogen production development; Kwansei Gakuin University has research on new functional materials using nanoscale structures; Yamanashi University is looking at materials for high-performance fuel cells, and many others have specialised activities.

3.2.2 Korea

Korea has a large market for stationary fuel cells, in particular, but does not have the mature native technology of the global leaders, other than perhaps in Hyundai, although there is major investment in building Korean development, manufacturing and installation capabilities. The Government has announced a US$2.3bn programme for hydrogen research, development, manufacturing capability, infrastructure and vehicles to 2022[42]. Several of the large Korean players are looking to capitalise on a possible FCH future. So far, this has resulted in acquisitions and partnerships with companies with the required technology from different regions (mainly North America). For example, Doosan acquired ClearEdge Power in 2014 and LG bought a controlling stake in Rolls Royce's Fuel Cell Systems. Kolon Industries has developed an MEA and mass production technology, after acquiring patents and research facilities from Samsung SDI and manufacturing technology via licence from W.L Gore and Associates Inc.[43].

Korea's globally important market for stationary fuel cells is strongly driven by its policy for renewable energy. The national Renewable Portfolio Standard obligates power generators to produce renewable electricity and the use of stationary fuel cells for this produces a multiple of renewable energy credits. The transport market has lagged stationary, though the US$2.3bn programme should make a significant impact. This is likely to dovetail with a roadmap announced by the Ministry of Environment which specifies the hydrogen fuel cell vehicle share to be more than 10% of new cars and 520 HRS by 2030[44]. This is an estimated 180,000 FCEVs.

CHP – micro-CHP and commercial

There is little deployment of mCHP and commercial units in Korea, which does not have the same level of policy support as Japan or Germany, though at one period it was pursuing a similar aggressive path to Japan. However, Korean companies have developed or are developing both mCHP and commercial scale technologies. Doosan does offer PEMFC CHP systems from 0.6 to 10 kW[45], running on natural gas. The technology was likely acquired from ClearEdge Power along with the PAFC technology. MiCo produces SOFC stacks and components, including cathode pastes for mCHP applications[46]. STX Heavy Industries has developed a 1kW mCHP system named 'encube' and S-Fuelcell (once GS Fuelcell) offers PEMFC CHP products in 1 or 5 kW residential units, and 6 or 10 kW modular units, using natural gas as fuel. It also has a PEMFC product running on hydrogen with a range of 1-10kW. HnPower, which currently produces reformers and reformer catalysts for natural gas, gasoline and diesel fuels[47], is developing a SOFC mCHP system running on natural gas and with a target power efficiency of 50%.

[42] Green Car Congress (2018) 'S Korea to invest $2.3B in hydrogen fuel cell vehicle industrial ecosystem over next 5 years' http://www.greencarcongress.com/2018/06/20180625-korea.html
[43] Business Korea (2016) 'Kolon Industries Secures Core Technology for Fuel Cell' Available at: http://www.businesskorea.co.kr/news/articleView.html?idxno=16404
[44] Hyundai (2016) 'FCEB Development Status in Korea' Available at: http://www.cte.tv/wp-content/uploads/2016/12/4_Jeon.pdf
[45] Doosan (Accessed May 2018) 'Fuel Cell System'. Available at: http://www.doosanfuelcell.com/kr/system/pemfc-600w/
[46] MiCo (Accessed May 2018) 'MiCo SOFC products'. Available at: www.micopower.com
[47] HnPower (Accessed May 2018) 'R&D'. Available at: http://www.hnpower.co.kr/kr/sub/product/type.asp

Large CHP and primary power

Korea does not yet have world-leading native stationary fuel cell capabilities, and has imported or acquired the technology to fulfil its policy commitments. Bloom Energy is manufacturing an 8.35 MW system for Korea South-East Power in the US. However, the large Korean power and infrastructure construction company, SK Engineering and Construction, will help to install the units[48]. LG Fuel Cell Systems acquired 51% of Rolls Royce Fuel Cell Systems in 2012, focusing on the development of large primary power SOFC stationary systems (1MW), fuelled by natural gas[49]. LGFCS are currently pre-commercial with most of the operations based in the US and UK, with only the manufacturing technology development in Korea[50]. POSCO power is Korea's leading stationary fuel cell manufacturer and has a total of 172 MW of operating capacity in 20 locations across Korea. POSCO Energy partnered with and invested in US-based MCFC firm FuelCell Energy in the past, but in 2018 announced its intent to leave the fuel cell business[51]. Doosan produces large commercial scale PAFC stationary systems, with power output up to 440kW. It has also built a PAFC manufacturing facility in Iksan, Korea that has a production capacity of 63MW per annum.

FCEV

Hyundai was the first company globally to release a production-line FCEV, the Tucson/ix35 and develops its own PEM fuel cell system. Its new Nexo FCEV SUV model was released early in 2018. Over 500 ix35's have been sold into Europe, since its release in 2013[52]. Hyundai FCEVs use high-pressure hydrogen tanks produced by Korean company Iljin Composities, one of few companies worldwide that has the capability to produce such tanks. It is looking to export the technology globally[53]. Kia, Hyundai's sister company, is looking to release its own commercial FCEV in 2020. An FCEV version of its Sportage SUV has been road tested. The companies share technology developed by their Eco Powertrain Development Centre[54], and since November 2017 the Hyundai-Kia Motor Group has been testing a manufacturing plant that will produce 3,000 FCEVs annually, aiming to support its new FCEV release and using 98% domestic core components, such as the electrodes. The MEAs, stacks and fuel cell systems will all be manufactured on-site[55].

FCEB

An ambitious partnership between the Korean government and Hyundai plans to replace Korean CNG buses with FCEBs. This is intended to build on Hyundai's PEM technology and experience in manufacturing FCEVs, as well as stimulating the production of fuel cell system components within Korea. There are currently 26,000 CNG buses in Korea and the claim is that these will be replaced at a rate of 2,000 per annum[56], with developments anticipated in 2019.

[48] Hydrogen Fuel News (2018) 'Bloom Energy to bring fuel cells to South Korea'. Available at: http://www.hydrogenfuelnews.com/bloom-energy-to-bring-fuel-cells-to-south-korea/8534074/
[49] LG Fuel Cell Systems (2013) 'Overview Presentation'. Available at: https://www.hydrogen.energy.gov/pdfs/htac_apr13_6_fleiner.pdf
[50] LG Fuel Cell Systems (June 2017) 'Program and Technology Update'. Available at: https://www.netl.doe.gov/File%20Library/Events/2017/sofc%20proceedings/monday/debellis-pandey.pdf
[51] FuelCell Energy, SEC Filing, 15 June 2018, available at: https://www.sec.gov/Archives/edgar/data/886128/000156459018015891/fcel-8k_20180615.htm
[52] Automotive News Europe (2018) 'Hyundai sees Germany as key market for Nexo fuel cell car'. Available at: http://europe.autonews.com/article/20180304/ANE/180309782/hyundai-sees-germany-as-key-market-for-nexo-fuel-cell-car
[53] FuelCellsWorks (2017) 'ILJIN Composites Selected as Supplier for Fuel Tanks for Hyundai Motor FCEV'. Available at: https://fuelcellsworks.com/news/iljin-composites-selected-as-supplier-for-fuel-tanks-for-hyundai-motor-fcev-fuel-cell-electric-vehi
[54] CNET – Roadshow (2017) 'Fuel Cell Cars – Kia promises hydrogen fuel cell car by 2020'. Available at: https://www.cnet.com/roadshow/news/expect-a-hydrogen-fuel-cell-kia-by-2020/
[55] [55] FuelCellsWorks (2017) 'Hyundai Mobis announces the world's first mass production of hydrogen parts facility'. Available at: https://fuelcellsworks.com/news/hyundai-mobis-annonces-the-worlds-first-mass-production-of-hydrogen-parts-facility
[56] Hyundai (2016) 'FCEB Development Status in Korea' Available at: http://www.cte.tv/wp-content/uploads/2016/12/4_Jeon.pdf

HRS

Korea's target to have 100 HRSs available in 2020, 230 in 2025 and 520 in 2030, and is driving native companies to develop HRS technology. Hyosung Corp. has developed the capabilities to construct HRS, with a few operational already, and will build the country's largest HRS (for 60 FCEVs and 2 FCEBs). An FCEV industry could produce demand for light weight carbon fibre materials, one of Hyosung's original strengths. EM Korea Co. also offers HRSs, with 350 and 700 bar options.

Maritime and inland boats

There is limited Korean fuel cell activity in maritime and shipping applications for propulsion, though work on APUs is being done by POSCO. However, Siemens PEMFC fuel cells are used in the Republic of Korea Navy's diesel-electric submarines, integrated by the submarine builder Hyundai Heavy Industries[57]

HGVs, trains and light rail

Little or no activity appears to be underway specific to HGV applications, trains or light rail.

Electrolysers

Deokyang, Korea's largest hydrogen supplier, is importing electrolyser technology from Norwegian company Nel ASA to access the growing market for HRS in Korea[58].

Hydrogen storage

Iljin Composities is supplying high-pressure plastic-composite storage tanks to the FCEV and FCEB manufacturers in Korea, mainly Hyundai. Iljin is only one of a handful of companies worldwide that can produce such tanks and is looking to export the technology globally[59].

Knowledge based actors

A great deal of research is underway in Korea, both in companies and especially at universities and institutes. From 2002-2015 Korea were responsible for 9% of all fuel cell patents, with only the US and Japan having a greater proportion[60]. In Ulsan city, a fuel cell system test facility has been established, to support fuel cell R&D[61].

The Korean Institute of Energy Research (KIER) is extremely active, with research focused on the technology and system of PEFC, SOFC and DMFC technologies, MEA design from low-cost and high-performance polymers to achieve high durability, and cylindrical/plate SOFC cells, stacks and system design and manufacturing technology[62]. The Korean Institute of Science and Technology (KIST) has research on MEAs

[57] Dominguez, G. (2018) 'RoKN's seventh KSS-2 submarine to start operations in May' Jane's 360. Available at: http://www.janes.com/article/77184/rokn-s-seventh-kss-2-submarine-to-start-operations-in-may

[58] Nel (2017) 'Nel ASA: Enters Korean hydrogen market through JV with Deokyang'. Available at: http://nelhydrogen.com/news/nel-asa-enters-korean-hydrogen-market-through-jv-with-deokyang/

[59] FuelCellsWorks (2017) 'ILJIN Composites Selected as Supplier for Fuel Tanks for Hyundai Motor FCEV'. Available at: https://fuelcellsworks.com/news/iljin-composites-selected-as-supplier-for-fuel-tanks-for-hyundai-motor-fcev-fuel-cell-electric-vehi

[60] Cleantech Group (2016) 'Clean Energy Patent Growth Index (CEPGI) – 2015 Year in Review' Available at: http://www.cepgi.com/2016/10/cepgi_2015_year_in_review.html

[61] International Partnership for Hydrogen and Fuel Cells in the Economy (2016) 'IPHE Country Update May 2016: Korea'. Available at: https://docs.wixstatic.com/ugd/45185a_a0e17a92e8b5439b97f6b23082643818.pdf

[62] Korea Institute of Energy Research (Accessed March 2018) 'New and Renewable Energy activities'. Available at: http://www.kier.re.kr/eng/03_activities/newrenewable03.jsp

across LT- and HT-PEMFC, MCFC, SOFC and PEM electrolysis, with focus points of low-cost catalysts, durable membranes and high-performance MEAs[63].

The Korea Institute of Ceramic Engineering and Technology (KICET) is focused on the development of SOFC materials, e.g. anode, electrolyte, ceramic interconnect material, sealant, ceramic support cell, and cathode, while Seoul National University has research areas in solid state ionics[64]. Yonsei University is looking at electrodes and fabrication[65] using core shell and nano-printing technology; Hanynag University at high temperature, low humidifying fuel cell membranes[66]. On the SOFC front, Inha University has research in tubular SOFC cells and stacks, as well as cathode materials; Pohang University of Science and Technology (POSTECH) is examining monolithic SOFC, defect chemistry, internal reforming, and alternative anode materials and Ulsan National Institute of Science and Technology (UNIST) is working in low-temp SOFC and electrodes[67].

Korea Advanced Institute of Science and Technology (KAIST) conducts computational analysis of SOFC and PEM stacks as well as diesel reformers[68], while the Research Institute of Science and Technology (RIST) has big ties with POSCO Energy and could almost be considered the research and development arm of the company. They work on planar SOFC, amongst other topics.

3.2.3 China

China has had strong fundamental research into FCH for at least two decades, and has also had some industrial activity, but only recently has it started to deploy sufficient numbers of units to be able to inform its local R&D in more depth. Strong fundamental research centres exist both in universities and in Key State Laboratories, and some of the university research is more applied, and acts almost as the R&D department of a company (for example Shanghai's Tongji University conducts a lot of applied R&D for Shanghai Automotive Industry Corporation (SAIC). Chinese technology is advancing rapidly but the majority of indigenous products still do not perform as well as overseas units, and so Chinese companies are setting up joint ventures both in China and abroad, as well as investing in companies in other countries, to speed up the inbound transfer of know-how and technology.

This industrial interest is driven partly by Chinese government policy goals. These are linked both to deploying clean technologies locally – to improve air quality, for example – and to developing indigenous high-value industries. FCH technologies are a stated focus area for both, as is summarised in the table below. FCEV and FCEB enjoy generous subsidies under the New Energy Vehicle support programme.

[63] Korea Institute of Science and Technology (Accessed March 2018) 'Fuel Cell Research Centre'. Available at: http://eng.kist.re.kr/kist_eng/?sub_num=591
[64] Sammes, N.M. (2013) 'Korean Overview of Academic SOFC Activities' POSTECH. Presented at Imperial College London 2013.11.06
[65] Sammes, N.M. (2013) 'Korean Overview of Academic SOFC Activities' POSTECH. Presented at Imperial College London 2013.11.06
[66] Hanyang University (Accessed April 2018) 'Research Achievements' (from 2016). Available at: http://www.hanyang.ac.kr/web/eng/pride05
[67] Sammes, N.M. (2013) 'Korean Overview of Academic SOFC Activities' POSTECH. Presented at Imperial College London 2013.11.06
[68] Sammes, N.M. (2013) 'Korean Overview of Academic SOFC Activities' POSTECH. Presented at Imperial College London 2013.11.06

Table 4: Chinese FCH development goals[69,70,71]

Goal	2020	2025	2030
Industry value, CNY billion/year	300 (~34 bn€)	-	1,000 (~115 bn€)
H2 production for energy use, billion m3/year	72	-	100
Vehicles on road, unit	• 5k* • 60% commercial and 40% car⁺ • 10k±	• 50k* • 20% commercial and 80% car⁺	• 1million* • 2million±
Other Infrastructure	50 train/tram demonstrations and shipping	-	3000km H2 pipeline
Refuelling stations	100	300	1000
FC system production capacity per company, units/year	1,000	10,000	100,000

*Note: The goals come out of roadmaps from associations and are not official policy goals. * From Developmental roadmap (2017); ⁺ From SAE (2016); ± From Blue Book (2016). The Blue Book is supposed to be official, but most China experts refer to the developmental roadmap (2017) figure*

The Chinese Ministry of Science and Technology plays an important linking and guiding role, and local and regional governments are increasingly active, with Rugao City, for example, aiming to become a ‘hydrogen city’.

Stationary fuel cells

Several Chinese companies work in stationary fuel cell applications, but it is not a government priority and installations have been limited, and primarily in backup and telecommunications power rather than CHP. Companies involved include Hephas Energy, Horizon, Troowin Power System Technology, and Hengjin Power Technology. These actors tend to work in smaller power ranges, well below 100kW, and little or no work is being done in higher power systems.

FCEV

Fuel cell vehicle-related R&D has been ongoing for at least two decades, but is increasingly a focus for the OEMs. SAIC has a long history in FCEV and now has a passenger car – ROEWE 950 – and a small bus – FCV80 – both of which feature in the official government tax free catalogue for new energy vehicles. FAW is developing fuel cell powertrains for vehicles, which might include passenger cars and buses[72], while Sunrise Power is supplying fuel cell stacks and systems to SAIC and FAW. Sunrise was founded in Dalian from technology developed at DICP (below) and so has access to very strong fundamental research strengths.

[69] CATARC (China Automotive Technology and Research Center), China Fuel Cell Vehicle Developmental Roadmap, 2017
[70] China Standardisation Committee, China Hydrogen Industry Infrastructure Development Blue Book, 2016
[71] SAE, Hydrogen Fuel Cell Vehicle Technology Roadmap, 2016
[72] http://company.cnstock.com/company/scp_gsxw/201711/4150459.htm

SinoHytec also has ongoing system development and strong overseas links. Aoxin, Dong Feng and Young Man all have truck production models. There were about 1,200 fuel cell trucks in China in 2017.

FCEB

China has a diverse and active bus sector, with manufacturers in every province. The bus sector has also attracted strong support for fuel cells. Even at this early stage, the New Energy Vehicle tax free catalogue provides a list of available vehicles[73]. For example, Foton, Feichi, King Long, SAIC, Shen Long, Young Man, Yutong and ZeV all have vehicle models registered. Dongfang Electric has jointly developed buses with Chengdu bus company using Dongfang's proprietary fuel cell technology. Zhongtong Bus Company and Broad Ocean jointly invested CNY500million in a research project on fuel cell development and commercialisation[74], and Zhongtong has produced three demonstration bus models ranging from 9-12m for urban and coach use[75]. FAW is developing its own fuel cell drivetrain, which could be used on its bus platform and SinoHytec, the fuel cell powertrain supplier[76], is thought to be supplying to Yutong, Foton, Feichi, ZeV, and Shenlong. About 250 buses were in China in 2017.

HRS and components

China has 18 HRS in operation, and at least another 21 under construction and in planning. They are mostly assembled by local consortia or companies often sourcing sub-systems or components from abroad. Peric, Sunwise, and Hydrosy all offer turnkey HRS. Snowman, Hanbell, and Beijing Tiangao are involved in hydrogen compressors, Tiangao claims to have China's first 100MPa compressor. The rapid development in hydrogen infrastructure includes station operators and project developers like Hyfun, Mingtian Hydrogen, Sino-Hytec, and the Vision group.

FC Forklifts, Maritime and inland boats

Little or no work is underway in these areas, though a few companies mention them as being of interest, including PearlHydrogen, Shenli High Tech[77] and SinoHytec[78].

Trains and light rail, Trams

CRRC Corp has signed a deal with Ballard to supply, develop, and commercialise fuel cell engines for low floor trams[79], and has an interest in trains.

Electrolysers

China has some electrolyser manufacturing capability, typically using relatively early-generation technologies. Alkaline systems are made by Peric, Ningbo Heli Hydrogen Energy Technology, Tianjin Mainland Hydrogen Equipment (THE) and Suzhou Jing Li Hydrogen Production Equipment.

[73] China State Administration of Taxation, New Energy Vehicle tax free catalogue, available from: http://www.chinatax.gov.cn/n810341/n810755/c1150779/content.html
[74] https://www.d1ev.com/news/shichang/54146
[75] http://www.chinabuses.com/buses/2017/0623/article_79291.html
[76] http://www.sinohytec.com/solution.php?id=4
[77] http://www.sinohytec.com/case.php?id=22
[78] http://www.sinohytec.com/solution.php?id=8
[79] http://ballard.com/about-ballard/newsroom/news-releases/2015/09/28/ballard-inks-$6m-deal-in-china-for-first-global-deployment-of-fuel-cell-powered-trams

Hydrogen storage

A few companies also produce hydrogen-compatible storage cylinders, all Type III (Type IV are not certified for use in China). The largest is Beijing China Tank Industry, but Shanghai Shen-Li, Zhangjiagang Furui, and Shenyang Silinda Anke New Technology both have developments in this area. Furui has a working Type IV prototype that is waiting for certification, it has been linked with Nedstack and Hymove[80].

Knowledge Based Actors

China has a lot of strong research capability. Some of the main knowledge-based actors include Tsinghua University, looking at PEFC, SOFC, DMFC technologies, automotive applications, and HRS. Other research focus incudes hydrogen production, storage, and integration in four relevant departments: the Institute of Nuclear and New Energy Technology and the Department of Energy and Power Engineering both focus on fuel cell technology, while the Department of Automotive Engineering and State Key Lab of Automotive Energy and Safety focus on vehicle integration. Tongji University has a research focus on low Pt catalysts, PEMFC, MEAs, automotive applications, and HRS[81]. It operates the State Key Laboratory of Clean Energy Vehicle & Powertrain Systems and the National Fuel Cell Vehicle & Powertrain System Research & Engineer Centre[82]. The China National Institute of Standardisation is an important actor, as fuel cell standards are written into subsidy policy. The Chinese Academy of Sciences has research on High-temp electrolysers, SOFC, MEA, PEMFC and automotive applications[83], and includes the Shanghai Institute of Ceramics, Changchun Institute of Applied Chemistry, Dalian Institute of Chemical Physics, and Ningbo Institute of Industrial technology. Wuhan University of Technology works on membranes, catalyst, cathodes, system integration, and simulation[84], and its offshoot, Wuhan Technology New Energy, is commercialising the above research.

Beijing Institute of Technology is working on catalyst, membrane, and vehicle integration; Kunshan Institute of Innovation, Nanjing University on catalyst, cathode, stack, fuel cell systems, vehicle integration, and scaling-up production[85]. Zhejiang University focuses on hydrogen energy storage and safety, and Southwest Jiaotong University on fuel cell materials and system integration. Foshan Hydrogen industry and new material development research institute is a local government research institute. Finally, Dalian University of Technology operates the State Key Laboratory of Fine Chemicals, focusing on Low Pt catalysts, cathodes, and a low temperature direct biomass fuel cell.

3.2.4 North America

The United States (US) and Canada have significant FCH activity at all levels of public and private research, government policy, and industry, while Mexico does not appear to be actively engaged. At the federal level, the US has maintained consistent funding levels around $100M (USD) at the US Department of Energy (DOE) in programs dedicated to addressing FCH technical barriers[86]. Some states have local funding, e.g. to increase fuelling infrastructure (California) or support local manufacturing development (Ohio and Connecticut). There is considerable collaborative R&D among the DOE National Laboratories, research universities, global and emerging companies, with a focus on shared pre-competitive R&D to address technical challenges

[80] http://www.china-hydrogen.org/fuelcell/mix/2017-12-21/7126.html
[81] http://www.sciencemag.org/sites/default/files/Tongji_Online-v2.pdf
[82] http://en.tongji.edu.cn/themes/10/template/laboratories.shtml
[83] http://www.nimte.cas.cn/research/research_field/nengyuan/fuel/, http://pemfc.dicp.ac.cn/,
[84] http://www.whut.edu.cn/chsweb/kxyj/gjjsys/201310/t20131028_105655.htm
[85] http://www.njukii.com/direction02.php?tid=1
[86] Program Record #17006, "Historical Fuel Cell and Hydrogen Budgets" (2017), https://www.hydrogen.energy.gov/pdfs/17006_historical_fuel_cell_h2_budgets.pdf

coordinated by the DOE. In Canada, the British Columbia province stands out as a fertile region of fuel cell innovation supported by efforts at research universities, the National Research Council Canada, Ballard, and the Automotive Fuel Cell Cooperation. Several North American companies are growing or at least are showing promising growth in their sales figures[87].

In contrast with Japan and some other regions, there is no clear linkage between Federal R&D funding and an articulated national policy to directly support or foster FCH markets in North America, though tax credits at the state and federal level support renewable energy installations. The Residential Renewable Energy Tax Credit was renewed in 2018 and is set to expire in 2021. It includes residential fuel cells and offers a maximum tax credit of 30% of the cost of the installed system. From 2009-2011 the American Reinvestment and Recover Act (ARRA) was a national-level effort to spur economic activity in the US, which has not been continued. Early market applications, material handling equipment[88] and backup power[89], demonstration projects were subsidised leading to a clear business case and a growing market for these applications. At the state level California has committed $200M over 10 years to building out hydrogen fuelling infrastructure, while a coordinated effort between Toyota, Air Liquide and four states in the Northeast (New York, New Jersey, Massachusetts, Connecticut, and Rhode Island) is expected to begin this year[90]. In addition to supporting fuelling infrastructure installation, there are state-level tax rebate incentives to support zero emission vehicles, including FCEVs.

Stationary fuel cells

Bloom Energy, FuelCell Energy, and Doosan Fuel Cell America (formerly ClearEdge and earlier part of United Technologies) are the dominant North American primary power system providers, all with offerings of multiple hundred kW and higher, while a handful of smaller companies focuses on developmental activities. These companies also dominate multi-hundred kW sales globally. Smaller-scale stationary and backup power fuel cells system providers such as Altergy have active and even growing sales, while continuing with demonstration projects.

FCEV

The FCEV market in North America is in its infancy. Sales are in the low 1,000s and slowly rising, almost all in California. AFCC, a high profile joint development effort which initially included Ballard, Daimler, and Ford is in the process of disbanding; however, there have been no public announcements. Meanwhile, GM and Honda are establishing joint manufacturing at the Brownstown, MI battery assembly plant. GM has a very active R&D programme, while Ford and, to much lesser extent, Fiat Chrysler Automobiles FCA support modest R&D which appears to be focused on proving the technical capabilities of FCH. In Canada, Ballard has reported joint ventures in China and licensing agreements globally, including with Audi, suggesting a trend towards growth mainly outside of North America.

FCEV support from the DOE is based on a clearly articulated set of technical targets that federal R&D funding is dedicated to supporting. There is also close collaboration between the DOE and automakers through

[87] https://www.energy.gov/sites/prod/files/2017/10/f37/fcto_2016_market_report.pdf
[88] Program Record #17003, "Industry Deployed Fuel Cell Powered Lift Trucks"(2017), https://www.hydrogen.energy.gov/pdfs/17004_industry_deployed_fc_bup.pdf
[89] Program Record #17004, "Industry Deployed Fuel Cell Backup Power"(2017), https://www.hydrogen.energy.gov/pdfs/17004_industry_deployed_fc_bup.pdf
[90] https://www.airliquide.com/united-states-america/air-liquide-plans-network-new-hydrogen-filling-stations-united-states

USCAR on setting technical targets and ensuring that the R&D portfolio is focused on addressing the automotive requirements.

FCEB

The US DOE and Department of Transportation (DOT) have established technical targets, which possibly reflects an acknowledgement that FCEBs are attractive from the perspective of fuelling infrastructure investment as they guarantee higher fuel throughput. There are a handful of bus demonstration programs throughout the United States and Canada, with US support for bus demonstration programs coming from the Federal Transit Administration. The primary North American fuel cell system providers are Ballard and Hydrogenics, with bus bodies made locally by companies such as New Flyer.

HRS

California has approximately 35 publicly accessible hydrogen refuelling stations, subsidised between 40%-85% of the total station cost by the state government. First Element, Air Liquide, and Linde are the dominant station installers. Throughout the rest of the US, there are scattered fuelling stations built to support demonstration projects and inaccessible to the public. Fuelling station build to support the Northeast corridor from Boston to Washington DC was scheduled to commence in 2018.

FC Forklifts

Around 700 FC forklifts were deployed with funding support under the American Recovery and Reinvestment Act (2009), which the DOE credits with generating more than 15,000 additional shipments without federal support. PEM forklifts have found a competitive niche in large warehouses due to faster refuelling times and lower total costs than battery-powered forklifts, and zero emissions compared with combustion powered forklifts. DMFC forklifts were also included in the 2009 subsidies but their commercial success has not been as marked. The primary fuel cell suppliers are Hydrogenics, Ballard, Hyster-Yale and Plug Power for PEM and Oorja for DMFC, though the latter has been very quiet for over a year.

Maritime and inland boats

There is little activity North America around maritime applications. A feasibility study was completed for a demonstration programme in the San Francisco bay; however, it is unclear if this might turn into a project.

HGVs

There is growing interest at DOE in both medium duty and heavy-duty fuel cell vehicles, and technical targets will likely be released this year to guide R&D funding towards growing that sector. Current on-road HGVs are limited to demonstration programs at the Port of Long Beach in California, but Nikola Motor Company has a public campaign selling its long-haul trucks and a hydrogen fuelling infrastructure to support it, with a reported commitment for 800 trucks from Anheuser-Busch. The trucks would use fuel cells from European-based PowerCell. Hydrogenics and Ballard are also working with established vehicle makers to develop fuel cell trucks.

Trains and light rail

There is limited rail activity in North America outside of feasibility studies conducted by city governments, including a substantial piece of work in Toronto. Ballard and Hydrogenics are developing partnerships in Europe and Asia to develop fuel cell systems for electric rail applications.

Electrolysers

Electrolysers were included in some of the California refuelling stations and electrolysers have been installed to support some of the FC forklift fleets. The major electrolyser developers are Hydrogenics, ProtonOnsite (now part of the Norwegian NEL group), and Giner, who have also got strong links to Europe through H2B2.

Hydrogen storage

Pressure vessel manufacturers are already profitable due to the mature CNG market. A number of global manufacturers have a North American presence including Hexagon (formerly Hexagon Lincoln) and Luxfer. Because composite overwrapped pressure vessels are considered a mature technology, there is limited government R&D support. In the US, the DOE supports R&D for advanced storage options such as sorbents and metal hydrides, and there is significant support for advancements in carbon fibre such as at the Carbon Fiber Composites Consortium at Oak Ridge National Laboratory and the Institute for Advance Composites Manufacturing Innovation.

Components

North America has a robust PEMFC component supplier base in many areas, with metal bipolar plates being one notable exception. W.L. Gore, 3M and DuPont are MEA suppliers with global reach, and AvCarb is one of a small group of global GDL suppliers. There are a few small start-up catalyst developers in North America and 3M continues to pursue its novel nano-structured thin film (NSTF) catalyst.

Knowledge-based actors

The DOE national labs in the US and National Research Council in Canada are world class research institutions with significant FCH leadership. In addition, world leading experts can be found at many research universities throughout the US and Canada. Clusters of PEM material development and characterisation activities are also found at sites of national resources such as synchrotron radiation sources at Argonne and Lawrence Berkeley National Labs, and one-of-a-kind imaging facilities at Oak Ridge National Lab. Oak Ridge National Lab is also the site of a pilot scale carbon fibre line used to test new carbon fibre manufacturing approaches and material formulations.

Testing

The DOE national labs, particularly the National Renewable Energy Lab (NREL) in Illinois and Argonne National Lab (ANL) in Colorado, do large scale testing and data collection efforts. NREL has coordinated with several demonstration programs and suppliers to develop anonymized composite data sets for fuel cells in a number of applications and hydrogen refuelling stations. Many of the national labs also operate under cooperative research agreements to perform tests for individual developers.

4 Criticality assessment and component cost basis

Results of the criticality assessment and the resulting cost breakdown analyses are presented in this section.

4.1 Critical components and selected critical components

The critical components identified using the screening methodology described in Section 2.5 are shown in Table 5. Further detail is included in Section 6, where the selected critical components are discussed per technology and more analysis on these critical components is presented.

Table 5: PEMFC critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
PEMFC	Supported catalyst	Specialised materials	6	7.14
	Membrane	Sub-component	6	7.11
	Membrane electrode assemblies	Sub-component	6	7.7
	Gas diffusion layer	Sub-component	6	7.12
	PEMFC stack	Sub-System	6	7.2
	PEMFC system	System	6	5.2, 5.4, 5.5, 5.6, 5.7
	Vehicle integration	Application	6	5.2
	Coated plate materials	Specialised materials	5	
	Membrane support	Specialised materials	4	
	Ionomer	Specialised materials	4	
	Bipolar plates	Sub-component	5	
	Air handling / recirculation	Sub-component	4	
	H2 sensor	Sub-component	4	
	Power electronics / inverters	Sub-system	4	
	Hydrogen tanks (see under Compressed Gas Storage (CGS))	Sub-system	4	5.9

Table 6: DMFC critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
DMFC	Supported Catalyst	Specialised materials	6	7.14
	Membrane	Sub-component	6	7.11
	Membrane electrode assemblies	Sub-component	6	7.7
	Gas diffusion layer	Sub-component	6	7.12
	DMFC stack	Sub-system	6	7.2
	DMFC system	Application	5	5.7
	Bipolar plates	Sub-component	5	
	Air handling / recirculation	Sub-component	4	
	Power electronics / inverters	Sub-system	4	

Table 7: SOFC critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
SOFC	Ceramic electrolytes	Sub-component	6	7.8
	Electrodes	Sub-component	6	7.8
	Seals	Sub-component	6	7.13
	Cell (EEA, MEA)	Sub-component	6	7.8
	SOFC stack	Sub-system	6	7.2
	Interconnectors	Sub-component	5	
	Porous metal layers	Sub-component	5	
	Fuel processors / reformer	Sub-system	5	5.10
	SOFC system	System	5	5.4, 5.5, 5.6
	Power electronics / inverters	Sub-system	4	

Table 8: PAFC critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
PAFC	Supported catalyst	Specialised materials	6	7.14
	PAFC stack	Sub-system	6	7.2.3
	Silicon carbide matrix	Sub-component	5	
	Bipolar plates	Sub-component	5	
	Seals	Sub-component	5	
	PAFC system	System	5	5.5, 5.6
	Desulphurisation	Sub-component	4	
	Deionisation	Sub-component	4	
	H2 sensor	Sub-component	4	
	Power electronics / inverters	Sub-system	4	
	Fuel processors / reformers	Sub-system	4	5.10

Table 9: AFC critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
AFC	AFC stack	Sub-system	6	7.2.2
	Electrode coatings / catalyst	Specialised materials	5	
	Seals	Sub-component	5	
	AFC system	System	5	5.5, 5.6
	Bipolar plates	Sub-component	4	
	Hydrogen sensors	Sub-component	4	
	Porous layer / membrane	Sub-component	4	
	Power electronics / inverters	Sub-system	4	

Table 10: MCFC critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
MCFC	MCFC stack	Sub-system	6	7.2.4
	Seals	Sub-component	5	
	Carbonate electrolyte sheet	Sub-component	5	
	Bipolar plates	Sub-component	5	
	MCFC system	System	5	5.6
	H2 sensors	Sub-component	4	
	Power electronics / inverters	Sub-system	4	

Table 11: AEL critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
AEL	Seals	Sub-component	5	
	Bipolar plates	Sub-component	5	
	Membrane / diaphragm	Sub-component	5	
	Porous conductive layer	Sub-component	5	
	AEL stack	Sub-system	5	7.3
	AEL system	System	5	5.8
	Anode	Sub-component	4	
	Cathode	Sub-component	4	
	Deionisation	Sub-component	4	
	Hydrogen sensors	Sub-component	4	
	H2 conditioning	Sub-system	4	
	AC-DC power supply	Sub-system	4	

Table 12: PEMEL critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
PEMEL	Catalyst	Specialised materials	6	7.14
	Membrane	Sub-component	6	7.11
	Membrane electrode assemblies	Sub-component	6	7.7
	PEMEL stack	Sub-system	6	7.3
	Ionomer	Specialised materials	5	
	Porous transport layer / gas diffusion layer	Sub-component	5	
	Bipolar plates	Sub-component	5	
	PEMEL system	System	5	5.8
	Membrane support	Specialised materials	4	
	H2 sensor	Sub-component	4	
	H2 conditioning	Sub-system	4	
	AC-DC power supply	Sub-system	4	

Table 13: SOEL critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
SOEL	Cell (EEA, MEA)	Sub-component	6	7.8
	Ceramic electrolytes	Sub-component	6	7.8
	Electrodes	Sub-component	6	7.8
	Seals	Sub-component	6	7.13
	SOEL stack	Sub-system	6	7.3
	Interconnectors	Sub-component	5	
	Porous metal layers	Sub-component	5	
	SOEL system	System	5	5.8
	H2 Sensor	Sub-component	4	
	H2 Conditioning	Sub-system	4	
	AC-DC power supply	Sub-system	4	

Table 14: Compressed hydrogen storage system critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
CGS	Carbon fibre	Specialised materials	5	7.15
	Regulators	Sub-component	4	
	Valve	Sub-component	4	
	Pressure vessel	Sub-system	4	7.4
	Tank system integration	System	2	5.9

Table 15: Hydrogen refuelling station critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
HRS	Dispensers / hose	Component	6	7.10
	H2 compressors	Sub-system	6	7.5
	H2 sensor	Sub-system	6	7.9
	HRS solution integration	System	5	5.3
	Flow Meters	Component	5	
	Precooling	Sub-system	4	

Table 16: Fuel processor / reformer critical components

Application	Critical component	Supply Chain Sector	Score	Section (if selected)
Fuel processors / reformers	Reactors	Sub-system	6	7.6
	Fuel processor integration /system provider	Integration	6	5.10
	PrOx catalyst	Specialised materials	5	
	Reactor catalyst	Specialised materials	4	
	Shift catalyst	Specialised materials	4	
	Desulphuriser	Sub-component	4	
	Reactor vessel	Sub-component	4	

4.2 Application cost data

In this section, cost breakdowns are provided. The section is organized first by chemistry, then application, followed by selected critical components. Cost breakdowns are reported with respect to projected annual production in 2024 and 2030 to provide a clear connection between cost breakdowns and the deployment scenarios in Section 8 where appropriate. For cases for which deployment scenarios were not projected, cost breakdowns are reported with respect to the generic annual productions provided in the source materials.

The majority of open literature in this area has been sponsored by the US DoE, thus many of the costs reported here come from those sources. While these are not perfectly translatable to European conditions (different labour rates, land prices etc.) they are used for two reasons. Firstly, the common sourcing means they are broadly comparable, and secondly, the variations are considered to be within the uncertainty margins that already affect these calculations. Raw materials prices, exchange rates and many other factors change over time, driving these costs higher or lower, but also changing relative costs within applications. For example, speculation may drive platinum prices higher, or currency fluctuations push them lower, but this cannot be captured in the analysis conducted here. Costs reported in US dollars are converted to Euro by the average daily exchange rate on 31 May 2018 (1 USD = 0.86 €).

As discussed in Section 2.4, the cost data are imperfect, but allow a common approach to the analysis. In many cases the cost data quoted are below the costs that industry believes are realistic in the near term, as they represent optimal outcomes and fully competitive supply situations. In many cases suppliers will have flexibility to ask for higher prices for materials and components in the near term, which will affect the raw costs for other components and for systems, driving the final cost higher.

The term “system” is used throughout the report as a generic term to mean, for example, a complete fuel cell power plant with all necessary balance of plant components. System design is specific to the application and, in most cases, the application vendor. For example, thermal management components for a combined heat and power plant are fundamentally different from those found in a fuel cell power plant for transportation. At the vendor level, the specific selection of fuel cell and balance of plant components are different between two automotive stack integrators with different design philosophies such as cathode-side gas pressure, operating temperature, and fuel starvation mitigation strategies as is common in designs currently on the road. Similar variations in design choices are seen throughout the many applications studied in this analysis. To simplify the cost breakdowns and draw out broad trends in the industry, the idea of a generic system has been assumed which allows for critical components to be assessed in an average way and non-critical components to be aggregated into a broad group of essential but otherwise neglected components.

A tiered supply chain structure has been assumed for applying mark-up at each supply chain level, with intermediate suppliers applying a mark-up to their added value. For example, an MEA manufacturer pays the catalyst, membrane, and GDL vendors’ mark-ups, but only applies a mark-up on the capital and labour associated with combining sub-components into a finished MEA (and not to the cost of the bought-in materials).

4.2.1 MCFC and PAFC

Installed MCFC and PAFC system costs for a 250 kW system are summarized in Table 17[91]. Installed system costs were provided by FuelCell Energy for MCFC primary power system for a 'stack' (which includes the steam methane reformer unit), balance of plant, and a category for conditioning, installation, and commissioning. Installed costs of a 250 kW PAFC primary power system were provided without further granularity.

Table 17: MCFC and PAFC system cost

System size	250 kW
MCFC (installed cost)	€ 3,600/kW
Stack	*€ 2,100/kW*
BOP	*€ 950/kW*
Conditioning, installation, commissioning	*€ 700/kW*
PAFC (installed cost)	€ 3,800/kW

4.2.2 PEMFC

PEMFC cost breakdowns are based on analyses of CHP, backup power, forklift power, light duty vehicle, and bus fuel cell systems performed by two separate groups. Costs of the critical components were surprisingly correlated across all applications reported by the two groups when normalized by power level and catalyst loading. An example of this correlation is shown in Figure 7 for membrane electrode assemblies (MEA). Throughout this report, the MEA is inclusive of the membrane, electrodes and gas diffusion layers (GDL). The data shown in Figure 7 are taken from multiple applications covering system power ranges 1kW – 250 kW. The data spread is largely due to differences in platinum loading which varies from 0.1 mg/cm^2 to 0.4 mg/cm^2 and differences in active to total area. This trend was observed for all the critical stack components. Balance of plant (BOP) cost correlations are application specific, as one would anticipate, yet have learning rate dependency on annual power production (i.e. €/kW) within the broad stationary and transportation application groups as shown in Figure 8.

[91] Remick, R., and D. Wheeler. "Molten Carbonate and Phosphoric Acid Stationary Fuel Cells: Overview and Gap Analysis." National Renewable Energy Lab. (NREL), Golden, CO (United States), September 1, 2010. https://doi.org/10.2172/990108.

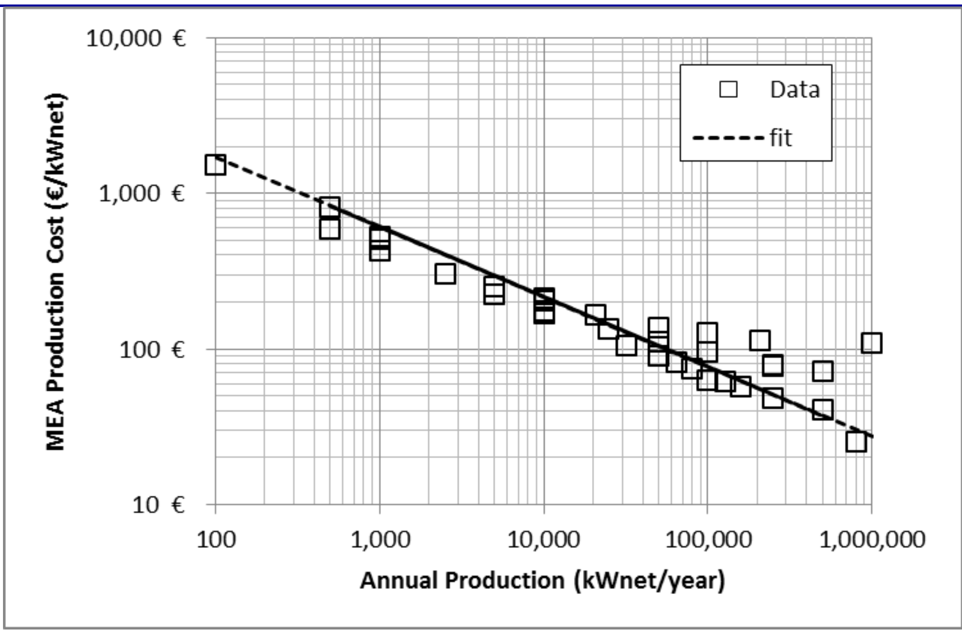


Figure 7: Example of MEA cost correlation across multiple PEMFC cost studies

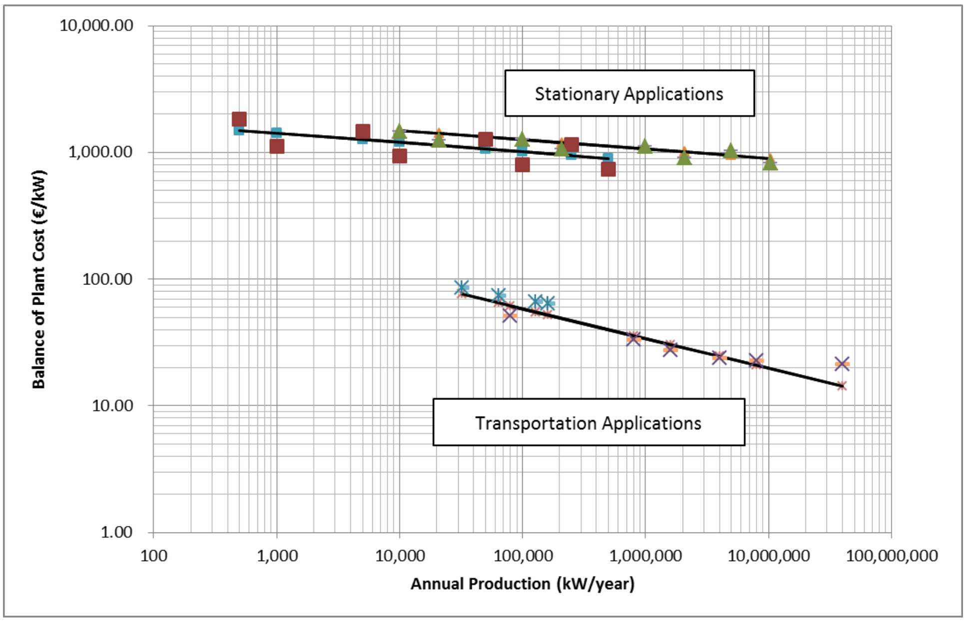


Figure 8: Example of BoP cost correlations across multiple PEMFC applications

4.2.2.1 Cars and light commercial vehicles

Cost breakdowns for cars with an 80 kW_{net} fuel cell system and 5 kg of on-board hydrogen storage are presented in Table 18[92]. Costs reported in the transportation studies have a number of caveats in addition to the general caveats described in Section 2.4. Costs are projected to very high volume (500,000 vehicles per year for light-duty vehicles) based on forward-looking, high-volume manufacturing and assume many components (such as next-generation catalysts) which are untested in the specific application. Integration includes ancillary stack components unique to the system (e.g. end plates with fittings for system-specific air and coolant handling components) and assembly.

[92] B. D. James, J. M. Huya-Kouadio, C. Houchins, and D. A. DeSantis, "Final Report: Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications (2012-2016)," Strategic Analysis Inc., Arlington, VA (United States), DOE-StrategicAnalysis-5236-1, Sep. 2016.

Table 18: PEMFC system cost breakdown for cars

	2024			2030		
	Low	Medium	High	Low	Medium	High
System cost	€ 11,000	€ 8.600	€ 7,700	€ 8,800	€ 7,000	€ 6,400
System integration	€ 290	€ 260	€ 250	€ 270	€ 240	€ 230
Storage system (Type IV)	€ 3,800	€ 3,100	€ 2,800	€ 3,100	€ 2,600	€ 2,400
BOP	€ 2,600	€ 1,900	€ 1,700	€ 2,000	€ 1,500	€ 1,300
Projected stack cost	€ 4,300	€ 3,300	€ 3,000	€ 3,400	€ 2,700	€ 2,400
Balance of stack	€ 100	€ 93	€ 89	€ 94	€ 85	€ 82
Bipolar plates (BPP)	€ 440	€ 400	€ 380	€ 400	€ 360	€ 350
Membrane electrode assemblies (MEA)	€ 2,800	€ 2,100	€ 1,800	€ 2,200	€ 1,700	€ 1,500
Membrane	€ 560	€ 410	€ 360	€ 430	€ 320	€ 280
Catalyst	€ 1,300	€ 1,000	€ 950	€ 1,100	€ 880	€ 810
Gas diffusion layer (GDL)	€ 370	€ 190	€ 140	€ 210	€ 110	€ 83

4.2.2.2 Buses

Buses with a 160 kW_{net} fuel cell systems and 40 kg of on-board hydrogen storage are summarized in Table 19. Stack components for all transport applications will have some similarity, though the need for longer lifetimes for heavy duty vehicles points towards some differentiation (perhaps increased catalyst loadings or graphite rather than metal bipolar plates).

Table 19: PEMFC system cost breakdown for buses

	2024			2030		
	Low	Medium	High	Low	Medium	High
System cost	€ 58,000	€ 51,000	€ 46,000	€ 46,000	€ 39,000	€ 34,000
System integration	€ 500	€ 480	€ 460	€ 460	€ 430	€ 410
Storage system (Type IV)	€ 33,000	€ 30,000	€ 28,000	€ 28,000	€ 25,000	€ 23,000
BOP	€ 6,700	€ 5,900	€ 5,200	€ 5,200	€ 4,300	€ 3,800
Projected stack cost	€ 18,000	€ 14,000	€ 12,000	€ 12,000	€ 9,100	€ 7,400
Balance of stack	€ 1,100	€ 1,000	€ 1,000	€ 1,000	€ 940	€ 900
Bipolar plates (BPP)	€ 750	€ 720	€ 690	€ 690	€ 650	€ 620
Membrane electrode assemblies (MEA)	€ 12,000	€ 9,400	€ 7,400	€ 7,600	€ 5,400	€ 4,200
Membrane	€ 1,400	€ 1,200	€ 1,100	€ 1,100	€ 920	€ 800
Catalyst	€ 2,700	€ 2,500	€ 2,300	€ 2,300	€ 2,000	€ 1,900
Gas diffusion layer (GDL)	€ 1,900	€ 1,500	€ 1,100	€ 1,100	€ 740	€ 550

4.2.2.3 Heavy goods vehicles

HGVs with a 200 kW_{net} fuel cell systems and 40 kg of on-board hydrogen storage are summarized in Table 20.

Table 20: PEMFC system cost breakdown for HGVs

	2024			2030		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
System cost	€ 58,000	€ 51,000	€ 46,000	€ 46,000	€ 39,000	€ 34,000
System integration	€ 710	€ 680	€ 660	€ 660	€ 620	€ 590
Storage system (Type IV)	€ 33,000	€ 30,000	€ 28,000	€ 28,000	€ 25,000	€ 23,000
BOP	€ 9,600	€ 8,500	€ 7,400	€ 7,500	€ 6,200	€ 5,400
Projected stack cost	€ 25,000	€ 21,000	€ 17,000	€ 17,000	€ 13,000	€ 11,000
Balance of stack	€ 1,500	€ 1,500	€ 1,400	€ 1,400	€ 1,300	€ 1,300
Bipolar plates	€ 1,100	€ 1,000	€ 980	€ 990	€ 930	€ 880
Membrane electrode assemblies (MEA)	€ 17,000	€ 13,000	€ 11,000	€ 11,000	€ 7,800	€ 6,000
Membrane	€ 2,000	€ 1,800	€ 1,600	€ 1,600	€ 1,300	€ 1,100
Catalyst	€ 3,900	€ 3,600	€ 3,300	€ 3,300	€ 2,900	€ 2,700
Gas diffusion layer (GDL)	€ 2,700	€ 2,100	€ 1,600	€ 1,600	€ 1,100	€ 780

4.2.2.4 Trains

Trains with a 300 kW_{net} fuel cell systems and 180 kg of on-board hydrogen storage are summarized in Table 21.

Table 21: PEMFC system cost breakdown for trains

	2024			2030		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
System cost	€ 200,000	€ 180,000	€ 170,000	€ 170,000	€ 140,000	€ 130,000
System integration	€ 1,100	€ 1,000	€ 980	€ 990	€ 930	€ 880
Storage system (Type IV)	€ 150,000	€ 140,000	€ 130,000	€ 130,000	€ 110,000	€ 100,000
BOP	€ 14,000	€ 13,000	€ 11,000	€ 11,000	€ 9,300	€ 8,000
Projected stack cost	€ 38,000	€ 31,000	€ 25,000	€ 26,000	€ 20,000	€ 16,000
Balance of stack	€ 2,300	€ 2,200	€ 2,100	€ 2,100	€ 2,000	€ 1,900
Bipolar plates (BPP)	€ 1,600	€ 1,500	€ 1,500	€ 1,500	€ 1,400	€ 1,300
Membrane electrode assemblies (MEA)	€ 25,000	€ 20,000	€ 16,000	€ 16,000	€ 12,000	€ 9,000
Membrane	€ 3,000	€ 2,700	€ 2,400	€ 2,400	€ 2,000	€ 1,700
Catalyst	€ 5,800	€ 5,300	€ 5,000	€ 4,900	€ 4,400	€ 4,000
Gas diffusion layer (GDL)	€ 4,100	€ 3,100	€ 2,400	€ 2,400	€ 1,600	€ 1,200

4.2.2.5 Small CHP

Cost breakdowns for 1 kW CHP systems are summarized in Table 22.[93]

[93] V. Contini et al., "Final Report - Stationary and Emerging Market Fuel Cell System Cost Assessment," Battelle Memorial Inst., Columbus, OH (United States), DE-EE005250, Apr. 2017.

Table 22: Cost breakdowns for small (1kW) PEMFC for CHP

	2024			2030		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
System cost	€ 2,600	€ 2,400	€ 2,300	€ 2,300	€ 2,100	€ 2,000
System integration	€ 310	€ 290	€ 280	€ 280	€ 260	€ 250
BOP	€ 1,900	€ 1,700	€ 1,700	€ 1,700	€ 1,600	€ 1,500
Projected stack cost	€ 470	€ 360	€ 320	€ 330	€ 300	€ 280
Balance of stack	€ 110	€ 100	€ 98	€ 99	€ 94	€ 90
Bipolar plates	€ 8	€ 7	€ 7	€ 7	€ 6	€ 6
Membrane electrode assemblies (MEA)	€ 250	€ 170	€ 150	€ 150	€ 140	€ 120
Membrane	€ 22	€ 18	€ 16	€ 16	€ 14	€ 12
Catalyst	€ 81	€ 76	€ 74	€ 73	€ 70	€ 67
Gas diffusion layer (GDL)	€ 63	€ 39	€ 33	€ 30	€ 22	€ 16

4.2.2.6 Commercial combined heat and power

Cost breakdowns for 100kW CHP systems are summarized in Table 23.[94] Cost breakdowns for larger CHP systems scale roughly with the power level as discussed in the sub-section overview.

Table 23: Cost breakdowns 100 kW PEMFC CHP

	2024			2030		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
System cost	€ 210,000	€ 200,000	€ 170,000	€ 180,000	€ 170,000	€ 160,000
System integration	€ 26,000	€ 25,000	€ 23,000	€ 24,000	€ 22,000	€ 21,000
BOP	€ 160,000	€ 150,000	€ 140,000	€ 140,000	€ 130,000	€ 120,000
Projected stack cost	€ 25,000	€ 20,000	€ 14,000	€ 14,000	€ 13,000	€ 11,000
Balance of stack	€ 150	€ 140	€ 130	€ 130	€ 120	€ 120
Bipolar plates (BPP)	€ 630	€ 610	€ 550	€ 570	€ 530	€ 490
Membrane electrode assemblies (MEA)	€ 18,000	€ 14,000	€ 10,000	€ 10,000	€ 9,100	€ 7,800
Membrane	€ 1,700	€ 1,500	€ 1,100	€ 1,200	€ 980	€ 800
Catalyst	€ 5,600	€ 5,400	€ 4,900	€ 5,100	€ 4,700	€ 4,400
Gas diffusion layer (GDL)	€ 4,300	€ 3,200	€ 1,700	€ 2,100	€ 1,300	€ 830

4.2.2.7 Backup power

Cost breakdowns for a 2.5 kW backup power system are summarized in Table 24.[95]

[94] V. Contini et al., "Final Report - Stationary and Emerging Market Fuel Cell System Cost Assessment," Battelle Memorial Inst., Columbus, OH (United States), DE-EE005250, Apr. 2017.
[95] V. Contini et al., "Final Report - Stationary and Emerging Market Fuel Cell System Cost Assessment," Battelle Memorial Inst., Columbus, OH (United States), DE-EE005250, Apr. 2017.

Table 24: Cost breakdowns for 2.5kW PEMFC for backup power

	2024			2030		
	Low	Medium	High	Low	Medium	High
System cost	€ 5,700	€ 5,100	€ 4,900	€ 5,200	€ 4,700	€ 4,300
System integration	€ 750	€ 710	€ 700	€ 720	€ 680	€ 640
BOP	€ 3,600	€ 3,400	€ 3,300	€ 3,400	€ 3,200	€ 3,100
Projected stack cost	€ 1,300	€ 1,000	€ 880	€ 1,000	€ 760	€ 600
Balance of stack	€ 30	€ 28	€ 28	€ 29	€ 27	€ 26
Bipolar plates	€ 18	€ 17	€ 17	€ 17	€ 16	€ 15
Membrane electrode assemblies (MEA)	€ 970	€ 720	€ 630	€ 740	€ 540	€ 420
Membrane	€ 65	€ 55	€ 52	€ 56	€ 47	€ 41
Catalyst	€ 41	€ 38	€ 38	€ 39	€ 36	€ 35
Gas diffusion layer (GDL)	€ 280	€ 190	€ 160	€ 200	€ 140	€ 100

4.2.2.8 Forklift trucks

Cost breakdowns for a 5 kW forklift power system are summarized in Table 25.[96]

Table 25: Cost breakdowns for 5kW PEMFC for fuel cell forklifts

	2024			2030		
	Low	Medium	High	Low	Medium	High
System cost	€ 3,500	€ 3,000	€ 2,600	€ 3,300	€ 2,700	€ 2,400
System integration	€ 1,400	€ 1,400	€ 1,300	€ 1,400	€ 1,300	€ 1,300
BOP	€ 49	€ 37	€ 30	€ 44	€ 32	€ 25
Projected stack cost	€ 2,000	€ 1,600	€ 1,300	€ 1,800	€ 1,300	€ 1,100
Balance of stack	€ 57	€ 54	€ 52	€ 56	€ 53	€ 51
Bipolar plates (BPP)	€ 34	€ 33	€ 31	€ 34	€ 32	€ 30
Membrane electrode assemblies (MEA)	€ 1,500	€ 1,100	€ 910	€ 1,300	€ 950	€ 750
Membrane	€ 110	€ 94	€ 83	€ 100	€ 86	€ 75
Catalyst	€ 170	€ 160	€ 160	€ 170	€ 160	€ 150
Gas diffusion layer (GDL)	€ 380	€ 280	€ 210	€ 340	€ 220	€ 170

4.2.3 DMFC

An FCHJU-supported cost analysis of 200 W stacks for auxiliary power units[97] is summarized in Table 26 without further refinement.

[96] V. Contini et al., "Final Report - Stationary and Emerging Market Fuel Cell System Cost Assessment," Battelle Memorial Inst., Columbus, OH (United States), DE-EE005250, Apr. 2017.

[97] Sgroi, Mauro Francesco, Furio Zedde, Orazio Barbera, Alessandro Stassi, David Sebastián, Francesco Lufrano, Vincenzo Baglio, Antonino Salvatore Aricò, Jacob Linder Bonde, and Michael Schuster. "Cost Analysis of Direct Methanol Fuel Cell Stacks for Mass Production." Energies 9, no. 12 (November 30, 2016): 1008. https://doi.org/10.3390/en9121008.

Table 26: DMFC system cost breakdowns

Production Rate	200	10,000
Projected Stack Cost	€ 2,884	€ 223
Membrane electrode assembly (MEA)	€ 651	€ 171
Catalyst	€420	€ 127
Membrane	€ 71	€ 27
Gas diffusion layer (GDL)	€ 160	€ 17
Bipolar plates (BPP)	€ 680	€ 3
Stack assembly	€ 29	€ 2

4.2.4 SOFC

SOFC cost breakdowns are based on analyses of small CHP, backup power, and large CHP systems. Similar to PEMFC described above, component costs are well correlated across multiple applications.

4.2.4.1 Small CHP

Cost breakdowns for 1 kW SOFC CHP systems are summarised in Table 27.[98]

Table 27: Cost breakdowns for small (1kW) SOFC for CHP

	2024			2030		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
System cost	€ 3,800	€ 3,700	€ 3,600	€ 3,600	€ 3,500	€ 3,400
System integration	€ 59	€ 48	€ 40	€ 45	€ 27	€ 19
BOP	€ 3,100	€ 3,100	€ 3,100	€ 3,100	€ 3,000	€ 3,000
Projected stack cost	€ 550	€ 510	€ 490	€ 500	€ 420	€ 410
Balance of stack	€ 190	€ 180	€ 170	€ 180	€ 160	€ 150
Interconnectors	€ 28	€ 26	€ 24	€ 25	€ 20	€ 17
Porous metal layers	€ 19	€ 18	€ 16	€ 17	€ 14	€ 12
Seals	€ 22	€ 20	€ 19	€ 19	€ 17	€ 17
Cell (EEA, MEA)	€ 160	€ 150	€ 150	€ 150	€ 130	€ 120

4.2.4.2 Medium/Large CHP

Cost breakdowns for 100kW CHP systems are summarized in Table 28.[99] Similar to PEMFC systems, cost breakdowns for larger SOFC CHP systems scale roughly with the power level as discussed in the sub-section overview.

[98] V. Contini et al., "Final Report - Stationary and Emerging Market Fuel Cell System Cost Assessment," Battelle Memorial Inst., Columbus, OH (United States), DE-EE005250, Apr. 2017.
[99] V. Contini et al., "Final Report - Stationary and Emerging Market Fuel Cell System Cost Assessment," Battelle Memorial Inst., Columbus, OH (United States), DE-EE005250, Apr. 2017.

Table 28: Cost breakdowns for medium (100kW) SOFC for CHP

	2024			2030		
	Low	Medium	High	Low	Medium	High
System cost	€ 120,000	€ 120,000	€ 110,000	€ 110,000	€ 110,000	€ 100,000
System integration	€ 7,900	€ 7,600	€ 7,000	€ 7,300	€ 6,800	€ 6,500
BOP	€ 74,000	€ 71,000	€ 64,000	€ 66,000	€ 62,000	€ 58,000
Projected stack cost	€ 42,000	€ 41,000	€ 40,000	€ 41,000	€ 40,000	€ 40,000
Balance of stack	€ 11,000	€ 11,000	€ 11,000	€ 11,000	€ 11,000	€ 11,000
Interconnectors	€ 2,200	€ 2,100	€ 2,000	€ 2,000	€ 1,900	€ 1,900
Porous metal layers	€ 1,900	€ 1,900	€ 1,800	€ 1,800	€ 1,800	€ 1,800
Seals	€ 1,500	€ 1,500	€ 1,400	€ 1,400	€ 1,400	€ 1,400
Cell (EEA, MEA)	€ 15,000	€ 15,000	€ 15,000	€ 15,000	€ 15,000	€ 15,000

4.2.5 Reformers

Reformer cost breakdowns for 250 kW CHP systems are summarised in Table 29 and Table 30 without further refinement. These units are meant to be included as balance of system components for CHP fuel cell systems and provide insight into high and low temperature reactors systems.

Table 29: Cost breakdown for PrOx reformer sized for 250 kW PEMFC

Production rate	100	1,000	10,000	50,000
PrOx catalyst	€ 38,000	€ 31,000	€ 26,000	€ 23,000
PrOx Reactor	€ 39,000	€ 33,000	€ 27,000	€ 25,000

Table 30: System cost for SMR reactor sized for 250 kW SOFC

Production rate	100	1,000	10,000	50,000
SMR Reactor	€ 6,800	€ 3,200	€ 2,500	€ 2,500

4.2.6 Compressed gas storage

4.2.6.1 Cars and lightweight vans

Cost breakdowns shown in Table 31 are for a single 700 bar Type IV pressure vessel with 5kgH2 storage capacity based on analysis supported by the DOE.[100]

Table 31: Cost breakdown for Type IV compressed gas storage for cars and light commercial vehicles

Production Rate	10,000	30,000	80,000	100,000	500,000
Carbon Fibre	€ 2,163	€ 2,163	€ 1,997	€ 1,893	€ 1,765
System Cost	€ 2,724	€ 2,568	€ 2,370	€ 2,266	€ 2,131

4.2.6.2 Tube trailer delivery

The study authors are not aware of publicly available cost analyses of Type IV tube trailer storage tanks. The results shown in Table 32 are estimated based on the cost breakdowns for cars. Since tank cost is dominated by carbon fibre and the mass of carbon fibre scales almost linearly with the mass of stored gas, this

[100] G. Ordaz, C. Houchins, and T. Hua, "Onboard Type IV Compressed Hydrogen Storage Systems-Cost and Performance Status 2015," U.S. Department of Energy (DOE), Hydrogen and Fuel Cells Program Record #15013, 2015. https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

approximation will be very close to the system cost. The costs below are estimated for H_2 tanks on-board the Hexagon TITAN® XL 40ft trailer with 985 kg storage capacity.[101]

Table 32: Cost breakdown for Type IV compressed gas storage for tube trailer delivery

Production Rate	10,000	30,000	80,000	100,000	500,000
Carbon Fibre	€ 373,827	€ 373,827	€ 345,131	€ 327,107	€ 304,933
System Cost	€ 470,781	€ 443,682	€ 409,548	€ 391,612	€ 368,208

4.2.7 Hydrogen Refuelling Stations

Refuelling station costs are reported in Table 33 and Table 34 for bus depot and retail refuelling station installations.[102] HRS costs represent average station costs reported by the NREL Hydrogen Station Cost Calculator and an expert workshop and, similar to other system cost breakdowns, are scaled from the cost data by station size.

Table 33: Cost breakdown for 4,000 kg/day bus HRS

	2024			2030		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
Bus Fleet HRS	m€ 33	m€ 30	m€ 28	m€ 30	m€ 27	m€ 26
Station integration	m€ 8.4	m€ 7.6	m€ 7.2	m€ 7.5	m€ 6.8	m€ 6.6
Balance of station	m€ 11	m€ 9.7	m€ 9.1	m€ 9.6	m€ 8.4	m€ 8.4
Compression	m€ 7.1	m€ 6.6	m€ 6.3	m€ 6.5	m€ 6.1	m€ 5.9
Dispensers	m€ 6.5	m€ 6.1	m€ 5.9	m€ 6.0	m€ 5.7	m€ 5.6

Table 34: Cost breakdown for 576 kg/day retail HRS (average size of deployed stations)

	2024			2030		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
Retail HRS	m€ 4.8	m€ 4.3	m€ 4.1	m€ 4.7	m€ 4.3	m€ 4.2
Station integration	m€ 1.2	m€ 1.1	m€ 1.0	m€ 1.1	m€ 0.98	m€ 0.94
Balance of station	m€ 1.6	m€ 1.4	m€ 1.3	m€ 1.4	m€ 1.2	m€ 1.1
Compression	m€ 1.0	m€ 0.95	m€ 0.91	m€ 0.94	m€ 0.88	m€ 0.85
Dispensers	m€ 0.93	m€ 0.87	m€ 0.85	m€ 0.87	m€ 0.82	m€ 0.80

4.2.8 Electrolysers

4.2.8.1 PEM electrolysis

PEMEL cost breakdowns for 500 kW system are presented in Table 35.[103]

[101] http://www.hexagonlincoln.com/download.aspx?OBJECT_ID=/upload_images/F04B2580B46A434AA680824B5871C798.pdf
[102] Mark Melaina and Mike Penev, "Hydrogen Station Cost Estimates," National Renewable Energy Lab,NREL/TP-5400-56412, September. 2013.
[103] Mark Ruth, Ahmad Mayyas, and Maggie Mann, 2017, "Manufacturing Competitiveness Analysis for PEM and Alkaline Water Electrolysis Systems", Fuel Cell Seminar and Energy Expo.

Table 35: PEMEL system cost breakdowns

	2024			2030		
	Low	Medium	High	Low	Medium	High
System cost	€ 330,000	€ 310,000	€ 300,000	€ 310,000	€ 290,000	€ 280,000
System integration	€ 54,000	€ 51,000	€ 49,000	€ 50,000	€ 47,000	€ 45,000
BOP	€ 160,000	€ 150,000	€ 150,000	€ 150,000	€ 140,000	€ 130,000
Projected stack cost	€ 110,000	€ 110,000	€ 100,000	€ 100,000	€ 100,000	€ 98,000
Balance of stack	€ 14,000	€ 13,000	€ 13,000	€ 13,000	€ 13,000	€ 13,000
Bipolar plates (BPP)	€ 4,600	€ 3,700	€ 3,400	€ 3,700	€ 3,300	€ 3,100
Membrane electrode assembly	€ 70,000	€ 53,000	€ 51,000	€ 53,000	€ 49,000	€ 48,000
Membrane	€ 18,000	€ 13,000	€ 13,000	€ 13,000	€ 13,000	€ 12,000
Catalyst	€ 29,000	€ 22,000	€ 21,000	€ 22,000	€ 21,000	€ 20,000
Porous transport layer / gas diffusion layer	€ 6,300	€ 4,600	€ 4,300	€ 4,500	€ 4,200	€ 4,100

4.2.8.2 Alkaline electrolysis

Cost breakdowns for 500 kW alkaline electrolysers are presented in Table 36.[104] The component sums are higher than the system cost due to rounding errors introduced in reporting to 2 significant figures.

Table 36: Alkaline electrolyser cost breakdown

	2024			2030		
	Low	Medium	High	Low	Medium	High
System cost	€ 240,000	€ 220,000	€ 210,000	€ 210,000	€ 190,000	€ 180,000
System integration	€ 160,000	€ 140,000	€ 140,000	€ 140,000	€ 120,000	€ 120,000
Stack	€ 85,000	€ 76,000	€ 75,000	€ 75,000	€ 66,000	€ 66,000

4.2.8.3 SO electrolysis

Detailed cost analysis for SOEL is not available in the public domain. However, the critical components and cost breakdowns for solid oxide electrolysis are largely comparable to SOFC, and cost analysis for SOEL was largely based on that of SOFC. Cost breakdowns for a 500 kW SOEL system are presented in Table 37. Due to the early commercialisation stage of SOEL today, and the limited number of system integrators, the uncertainty over future development of SOEL technology is higher than in other electrolyser chemistries. Therefore a conservative approach has been taken regarding future cost. However, should SOEL be established in the market as a proven alternative, costs could fall more drastically than depicted here.

[104] Schmidt, O., A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few. "Future Cost and Performance of Water Electrolysis: An Expert Elicitation Study." International Journal of Hydrogen Energy 42, no. 52 (December 28, 2017): 30470–92. https://doi.org/10.1016/j.ijhydene.2017.10.045; Mark Ruth, Ahmad Mayyas, and Maggie Mann, 2017, "Manufacturing Competitiveness Analysis for PEM and Alkaline Water Electrolysis Systems", Fuel Cell Seminar and Energy Expo.

Table 37: SOEL cost breakdowns

	2024			2030		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
System cost	€ 780,000	€ 730,000	€ 700,000	€ 730,000	€ 680,000	€ 650,000
System integration	€ 48,000	€ 46,000	€ 45,000	€ 46,000	€ 43,000	€ 42,000
BOP	€ 470,000	€ 450,000	€ 430,000	€ 440,000	€ 420,000	€ 390,000
Projected Stack Cost	€ 260,000	€ 240,000	€ 230,000	€ 240,000	€ 220,000	€ 220,000
Balance of stack	€ 66,000	€ 62,000	€ 60,000	€ 61,000	€ 58,000	€ 57,000
Interconnects	€ 16,000	€ 15,000	€ 13,000	€ 14,000	€ 13,000	€ 12,000
Porous metal layers	€ 12,000	€ 11,000	€ 11,000	€ 11,000	€ 10,000	€ 9,800
Seals	€ 13,000	€ 9,800	€ 8,800	€ 9,600	€ 8,300	€ 7,700
Cells	€ 89,000	€ 83,000	€ 80,000	€ 82,000	€ 79,000	€ 77,000

4.2.9 Liquid carriers

Cost breakdowns are proposed for two liquid carriers, ammonia and formic acid, based on preliminary analysis presented by Argonne National Lab[105]. The results should be considered preliminary as they are back calculated from a limited set of assumptions reported in the preliminary results. Specifically, costs were reported for ammonia production and decomposition plants capable of processing 1,500 kg H_2/day in \$/kg H_2. The plant costs shown in Table 38 and Table 39 are based on 1,500 kg of hydrogen produced per day with an assumed 2 year payback period and 365 days per year operation. The integrator cost is based on the average integrator fraction (26%) from the hydrogen refuelling station cost breakdowns reported above.

Table 38: Cost breakdowns for ammonia production and decomposition

	Ammonia production	Ammonia decomposition
Reactor	€ 650,000	€ 440,000
Integrator	€ 170,000	€ 120,000
Total	€ 820,000	€ 570,000

Table 39: Cost breakdowns for formic acid production and decomposition

	Formic acid production	Formic acid decomposition
Reactor	€ 990,000	€ 440,000
Integrator	€ 260,000	€ 120,000
Total	€ 1,200,000	€ 560,000

[105] RK Ahluwalia, "System Level Analysis of Hydrogen Storage Options", U.S. Department of Energy Hydrogen and Fuel Cells Program Annual Merit Review, June 2018. https://www.hydrogen.energy.gov/pdfs/review18/st001_ahluwalia_2018_o.pdf

5 Mapping of European FCH supply chains by application

5.1 Introduction

The different supply chains for components and applications overlap in many ways, and so this analysis has been approached from two directions. Assessing the supply chains by application allows the identification of actors who could deliver a specific final product into a market, but does not easily allow the analysis of strengths and weaknesses *within* that chain. Assessing them by technology allows the identification of strengths and weaknesses in the chain but not of the importance or accessibility of a final market. The analysis and findings in this section are focused at the system/application level, while Section 6 is arranged by technology.

5.1.1 SWOT analysis

An analysis of EU strengths, weaknesses, opportunities and threats (SWOT) is provided for each application's supply chain. Because the markets for the different applications are mostly nascent, issues related to the external environment are included as well as specific supply chain aspects. Strengths and weaknesses are considered to exist within the specific application and its European supply chain (e.g. that Europe has world-leading component suppliers or is lacking a specific link in the chain) while opportunities and threats come from the external context (e.g. that China may rapidly develop competitive technologies and displace European companies, or that the concerns over diesel emissions may offer FCEV opportunities).

5.1.2 Gap assessment

The interdependent nature of the applications and components means that a very detailed gap analysis is both hard to conduct and to interpret. The approach taken here is therefore discursive, highlighting the main areas of difference in capabilities between Europe and leading global regions, as discussion text underneath each SWOT table.

5.2 Fuel cell transport applications using PEMFC

Although the final integrators are typically quite different, and some of the components have different specifications, the supply chain for cars, vans, heavy goods vehicles, buses and forklifts has a lot of commonality. To avoid undue repetition each application is discussed based on the generalised supply chain diagram shown in Figure 9. For some of the applications (e.g. ships) other fuel cell chemistries are also applicable, but are usually not used for propulsion but rather for hotel loads (similar to stationary uses), which is why these are not included under transport. As explained in Section 4.1, some components have been selected for further analysis and are highlighted in the diagrams.

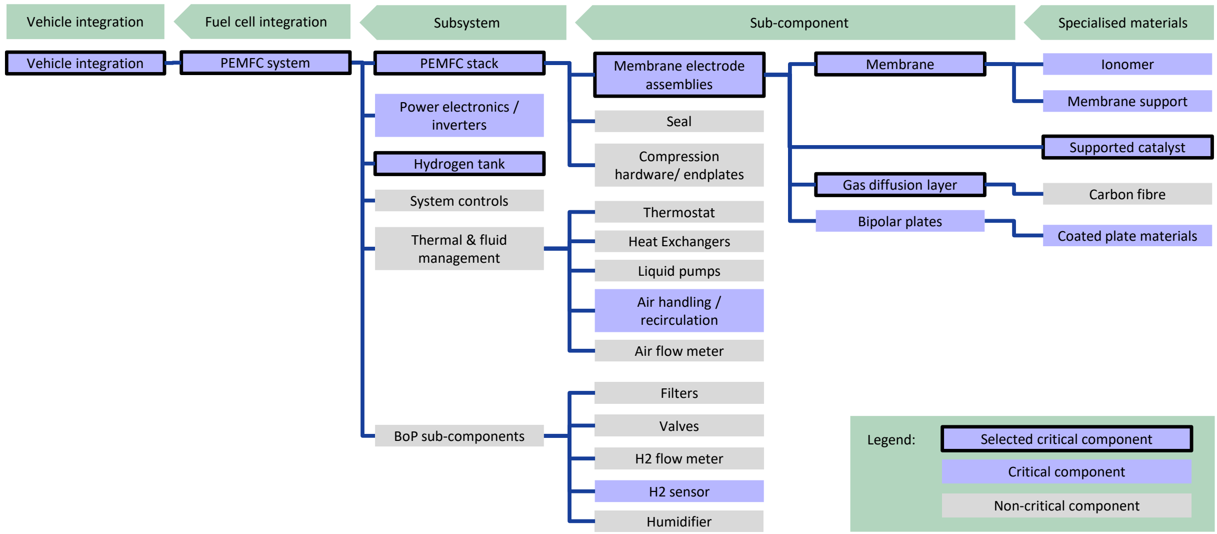


Figure 9: Fuel cells for transport supply chain structure

Critical components in PEMFC transport applications were in identified based on published cost analysis for fuel cell cars and light commercial vehicles (FCEV) and fuel cell electric buses (FCEB), which is generally transferrable to the other PEMFC transport applications: Forklift trucks, fuel cell heavy goods vehicles (HGV), trains and light rail, and maritime and inland boats. The critical components are shown in Figure 9 and listed with their individual scoring in Table 40. Within the stack, the catalyst layers, the membrane, gas diffusion layers and bipolar plates are the main cost contributors today and are expected to remain so.[106] Among specialised materials, supported catalysts have been identified as most critical in terms of supplier choice. Within the balance of plant components, air compressors and hydrogen recirculation are major cost contributors[107], but are not selected as most critical. The hydrogen tank adds considerably to overall costs in all three vehicle types as well[108], and is discussed in the hydrogen storage section. As with other electric drivetrains, power electronics are a major cost factor, but since they are not unique to FCH applications their supply chains are not evaluated here. Availability and acceptable performance of hydrogen sensors is currently limited, but they are not a major cost item overall so are not selected as most critical.

[106] Fuel Cell System Cost - 2015 - DOE Hydrogen and Fuel Cells Program Record #15015. p.8
URL: https://www.hydrogen.energy.gov/pdfs/15015_fuel_cell_system_cost_2015.pdf
[107] Fuel Cell System Cost - 2015 - DOE Hydrogen and Fuel Cells Program Record #15015. p.9
URL: https://www.hydrogen.energy.gov/pdfs/15015_fuel_cell_system_cost_2015.pdf
[108] James et al. 2013 'Hydrogen Storage Cost Analysis' https://www.hydrogen.energy.gov/pdfs/review13/st100_james_2013_o.pdf

Table 40: PEMFC for transport applications critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Supported catalyst	Specialised materials	6	7.14
Membrane	Sub-component	6	7.11
Membrane electrode assemblies	Sub-component	6	7.7
Gas diffusion Layer	Sub-component	6	7.12
PEMFC stack	Sub-System	6	7.2
PEMFC system	System	6	5.2
Vehicle integration	Application	6	5.2
Coated plate materials	Specialised materials	5	
Membrane support	Specialised materials	4	
Ionomer	Specialised materials	4	
Bipolar plates	Sub-component	5	
Air handling / recirculation	Sub-component	4	
H2 sensor	Sub-component	4	
Power electronics / inverters	Sub-system	4	
Hydrogen tanks (see under Compressed Gas Storage (CGS))	Sub-system	4	5.9

5.2.1 Application introduction for cars and light commercial vehicles (FCEV)

Fuel cell cars and light commercial vehicles (here denoted as FCEV) are considered together in this section as the drivetrains are very similar, and some overlap exists within the integrators also. The FCEV chain includes both major automotive companies and smaller entrepreneurial organisations. It does not include other types of vehicle such as two-wheelers. The FCEV application divides into several sectors, stretching from true OEM vehicles designed specially and built using an automotive supply chain, to converted vehicles based on existing models.

The leading OEM integrators for FCEVs are in Asia, with Hyundai, Toyota and Honda all well advanced. Daimler is currently the only European OEM with a 'commercial' product, in very limited production, though Audi, BMW, Fiat and others have suggested that they may have vehicles around 2020. Europe does however have several entrepreneurial integrators targeting different applications: French company Symbio offers converted Renault Kangoo vehicles with range-extender fuel cells, German company Streetscooter intends to produce FC range-extender electric vehicles and UK-based Riversimple has designed a car from the ground up.

5.2.1.1 FCEV supply chain description

There is limited specialisation of the critical components among the different transportation applications. For example, the membrane for an FCEV might differ modestly from a membrane designed for an FCEB or HGV. These differences, however, are well within the capability of a single supplier. This is true of all the critical fuel cell components with the exception of the bipolar plates which can be subdivided into metal and graphite. While metal bipolar plates can be found in all transportation applications, graphite has found limited appeal in FCEVs due to the strict volume and weight requirements of this application. It is however possible that it will be favoured in heavy-duty applications where weight and volume are slightly less restricted and the longer life of graphite is an advantage. Consequently, it is reasonable to expect that the only major divergence in supply chain between the different transportation applications will occur at the application integrator, at least in the near term.

The majority of companies that supply components shown on the right hand side of Figure 10 (See Section 6.2 for specific companies in selected critical components) specialise in only one component, though membrane electrode assemblies may be produced by companies with membrane or catalyst expertise. Stack integrators are sometimes also system integrators, and system integrators may sometimes also be vehicle integrators. The supply chains are international, and so any actor may buy from one or more companies in or outside the EU. Exclusive arrangements are rare or non-existent, as this would increase risk, though in practice often only one company will supply the exact component required. Much of the supply chain is immature, and sparsely populated with credible players globally.

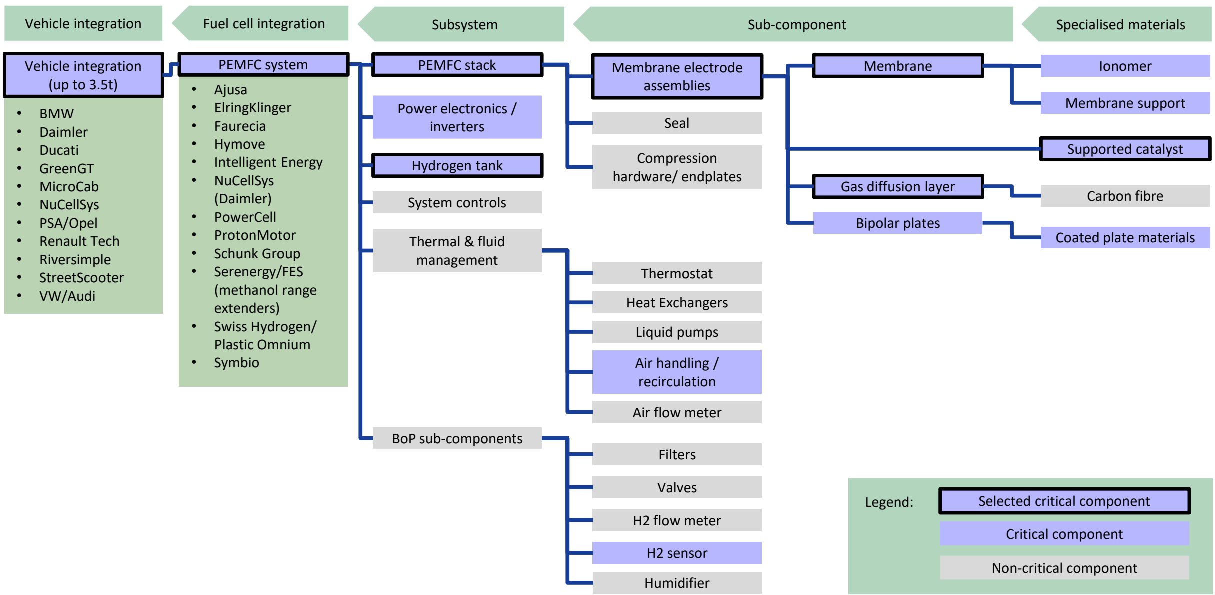


Figure 10: Fuel cells for light duty vehicles supply chain structure with European integrators

Relatively few KBAs play a strong role at the final integration level of FCEV, though strengths exist throughout the broader supply chain. Expertise is generally strongest in regions with an automotive industry, though not exclusively, with actors spread across Germany, Italy, France, Spain, the UK and several other countries.

5.2.1.2 FCEV system-level SWOT / gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 41 below shows the results of the SWOT analysis for FCEVs as a whole, carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of FCEVs*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 41: SWOT of European FCEV supply chain

STRENGTHS	WEAKNESSES
• Several strong potential FCEV integrators, though few of these have their own stack technology • Some strong independent stack developers and producers engaged with and looking to supply transport fuel cells • The mix of large corporate and small entrepreneurial entities means that different markets and niches could be addressed • High value specialist PEM stack component suppliers with strong IP and established global relationships • Deep automotive supply base capable of developing and supplying FC-relevant components • Strong research base in fuel cells and general automotive technology	• EU vehicle companies are not amongst the 3 market leaders in FCEV deployment[109] and have delayed vehicle launch several times, so some suppliers have reduced activity • Some reliance on non-EU companies for the tank and material (specialised C fibre) • European countries have articulated limited national visions compared with Japan[110], Korea, China[111], so less expectation or opportunity for OEMs to lead • Slow development of appropriate standards for HRS (e.g. safety zones, failsafe requirements) holds back infrastructure build and affects vehicle rollout in some cases • Fragmented support for FCEVs and infrastructure across Europe means deployment of vehicles is also piecemeal, with no early critical mass which would help to support HRS economics • While 700 bar compressed H2 in pressure vessels is the leading on-board supply method, other methods (lower pressures, LH2, etc.) fragments the required HRS dispensing methods and inhibits FCEV adoption

[109] E4tech Fuel Cell Industry Review 2016 http://www.fuelcellindustryreview.com/
[110] METI Strategic Roadmap for Hydrogen and Fuel Cells 2016 http://www.meti.go.jp/english/press/2016/0322_05.html
[111] Ju Wang, 2016 'Overview of Hydrogen and FCB in China' China Automotive Technology & Research Center http://www.cte.tv/wp-content/uploads/2016/12/5_WangJu_FINAL.pdf

OPPORTUNITIES	THREATS
• Tightening EU, national and local regulations for air quality and CO_2 plus FCEV-oriented deployment support could pull through (EU) FCEVs • Strong and growing interest in large-scale hydrogen for other applications could raise interest in transport options • Technical synergies with other xEV product platforms under development by most EU vehicle companies (e.g. increased numbers of FC range extenders) • Experience in composite materials in other industries could be extended for tanks • Cities and regions could build entrepreneurial activity further by favouring local solutions • Chinese desire for JVs and technology transfer could be exploited by EU companies to develop export markets	• Strong BEV interest and slow FCEV uptake in the EU may discourage stronger supply chain engagement or cause some companies to drop out • Carbon fibre cost fluctuates with oil prices and thus significantly higher oil prices would lead to higher H_2 storage system cost, off-setting some of the reinvigoration into FCEV that rising oil prices would otherwise have • The Japanese technology lead may extend with 2nd generation FCs, making EU suppliers and integrators vulnerable • Recent Chinese entry to FCEVs could – in time – lead to low cost supply of components and displace EU suppliers • One or two major players leaving the market for strategic reasons could significantly weaken supply options for the whole sector globally

As the SWOTs suggest, overall the EU ranks on a par with other regions in FC cars – though more of the activity is with smaller integrators and in the supply chain than with the major European OEMs. The latter lag the one or two leading companies in Japan and Korea, and most OEMs will not have vehicles available before 2020, so the early supply gap is being filled by Asian OEMs. However, stack component suppliers are particularly strong, with catalyst, bipolar plates, GDL and MEA technology all world-class. It must be noted however that automotive supply chains are possibly the most rigorous of any in terms of quality and cost, and most of these players are multinationals, with production facilities worldwide.

Hydrogen storage is covered in more detail in Section 5.9. Compressed hydrogen tanks are a high cost item with few suppliers. Europe has some companies present in this market, but the supply of high quality carbon fibre material, which is critical for the manufacturing process, is dominated by Asia, and so tank manufacture is currently a bottleneck in the vehicle supply chain as well as a relatively high-cost item, and can be considered a gap.

Japan and Korea lead the global automotive sector in terms of production and do use European suppliers when appropriate, though are very focused on developing local alternatives, and specifically support their local supply chain actors[112]. China is now emerging as a serious market for transport fuel cells and has a stated objective to develop an indigenous supply chain in the longer term, as well as building manufacturing and assembly capacity locally. In the near term, Chinese firms are looking for JVs and technology transfer as they ramp up production, evidenced by the strong relationships held by Ballard, Hydrogenics and other non-European fuel cell manufacturers in China; the engagement of Impact Coatings of Sweden for a specialist coating line[113]; and initiatives such as the German-based company Fuel Cell Powertrain, which was started

[112] Patrick Fullenkamp, 2016, ‘U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competitiveness Analysis’ https://www.hydrogen.energy.gov/pdfs/review16/mn014_fullenkamp_2016_o.pdf
[113] E4tech Fuel Cell Industry Review 2016 http://www.fuelcellindustryreview.com/

using Chinese investment [114]. Other European firms could potentially use this opportunity to develop technology and export markets and also to gather valuable in-use performance data.

5.2.2 Application introduction for FC Buses

Fuel cell buses (denoted as FCEB) are assessed in this section. The supply chain diagram for these applications contains many common components and suppliers, as shown in Figure 9. The FCEB chain includes component suppliers shared with other PEMFC applications, dedicated stack and system suppliers as well as established bus makers. For fuel cell dominant architectures, analysis suggests power levels for light-, medium-, and heavy-duty vehicles will have a high degree of modularity in early markets. Indeed, modular stacks in the 80-100 kW size range cover the full spectrum of weight classes. Examples of this strategy include Ballard and Toyota ~100kW stacks used in cars (Toyota), and two ~100 kW stacks used for buses and HGVs.

5.2.2.1 FC bus supply chain description

As discussed previously, there is limited specialization of the critical components among the different transportation applications, though for buses (Figure 11) it is possible that the membrane might differ modestly from a membrane designed for an FCEV, and graphite may be preferred for the bipolar plate. These differences, however, are well within the capability of a single supplier. This is true of all the critical fuel cell components. Consequently, it is still reasonable to expect that the major divergence in supply chain between the different transportation applications will occur at the application integrator, at least in the near term.

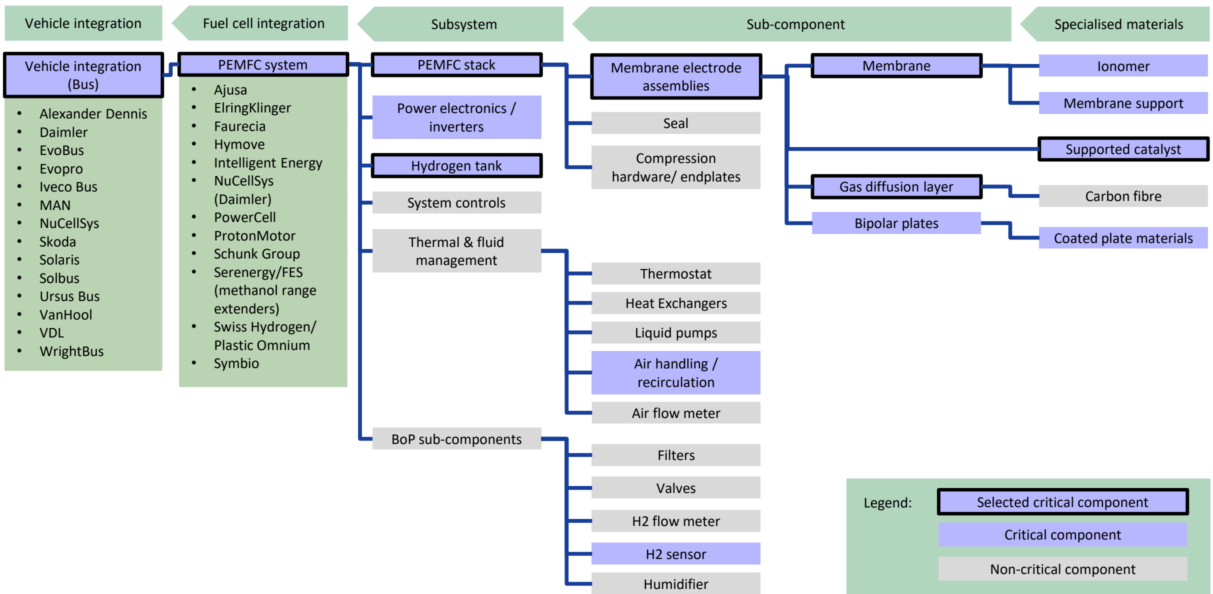


Figure 11: Fuel cells for buses supply chain structure with European integrators

As with FCEVs above, relatively few KBAs are active at the integration level, with the skills base typically more concentrated in earlier supply chain stages. Since bus demonstration projects have been a notable European strength for a long time, expertise has been developed in monitoring and analysis of performance and of degradation.

[114] https://www.fuelcellpowertrain.de/downloads/Pressemitteilung%201%20FCP_Engl.pdf

5.2.2.2 FC bus system-level SWOT / gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 42 below shows the results of the SWOT analysis for FCEBs carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of FCEBs*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 42: SWOT of European FCEB supply chain

STRENGTHS	WEAKNESSES
• Good supply base, including potential EU stack suppliers and strong automotive component manufacturers • All of the components could be sourced in the EU though tanks are a bottleneck • Some subcomponent suppliers are globally competitive and components go into non-EU stacks (which may then come back to the EU) • Increasing number of integrators both at system and bus level, with different platforms (e.g. bus length) and offerings (e.g. level of hybridisation) meeting different requirements • Conditions for FCEB deployment in the EU are strong due to strong city and regional support (including regulations) for ZEBs and specifically FCEBs, plus joint procurement and other collaborative initiatives[115] • Space requirements and refuelling times for FCEBs can be better than battery buses	• Stacks from EU suppliers who might supply buses have not yet proven long lifetimes, so buyer confidence is less than for non-EU suppliers • Reliance on non-EU companies for much of the tank and its material (specialised C fibre) means costs can be high and supply to other regions is sometimes prioritised • EU-dominated supply chain may not develop, as EU is not leading in stack manufacture and tank production may remain more competitive elsewhere • System costs are high and hard to reduce, so finding the right financing remains important • Demand is dispersed and each location has different requirements for buses, so even large orders require customisation and cost reduction is hampered[116] • Space for HRS is limited and H_2 logistics not simple in many cities, limiting bus demand

[115] Zero Emission Bus conference - 10th edition International FCB workshop, London, 2016 http://chic-project.eu/newsevents/events/zero-emission-bus-conference-10th-edition-international-fcb-workshop-london
http://www.cte.tv/zebc_presentations/
[116] FCH JU 2015 'Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe'
http://www.fch.europa.eu/sites/default/files/150909_FINAL_Bus_Study_Report_OUT_0.PDF

OPPORTUNITIES	THREATS
• Further commitments by more cities to better air quality should boost the market. • A common bus design (or at least common fuel cell system) could allow pooling of orders and significantly reduced bus cost in the near term • Integration is a high part of the cost. If it could be optimised, perhaps through support, EU manufacturers could compete better • Composite material expertise in other industries could be exploited • China's desire to deploy buses and to build capability offers EU export opportunities • Stack suppliers could enter into JVs with China to demonstrate their lifetime and performance in a market with more demand • Some bus integrators could supply non-EU regions with current technology, and increase their markets	• If considerably better battery buses are developed, FCEB may not retain or grow a market • As administrations change, regulations such as those for ZEBs may not remain in place long enough to force technology uptake • If costs do not come down, local authorities may not be able to justify budgets for FCEBs • China is developing capabilities rapidly and may be able to supply globally in a few years[117] • Carbon fibre for tanks comes from other regions and supply is short, so higher value markets such as aircraft may continue to be prioritised

Europe is well placed in fuel cell bus development, having seen the majority of the early roll-out, though China is now deploying more vehicles. Both European and Chinese manufacturers have been largely dependent on Canadian technology from Ballard and Hydrogenics for stacks and subsystems, though Europe has suppliers (e.g. Proton Motor) developing these capabilities and who could fill this gap if the technology can be suitably well proven. Costs remain high, in part due to small historical order numbers, though this is changing through larger orders. These larger numbers are typically the result of local, national or international programmes, such as run by the FCHJU. Gaps remain in areas such as integration know-how and capacity, as the small numbers of buses made in Europe thus far have mainly been individually hand-built. In many places a gap also exists in bringing together the right funding to allow local bus operators to take advantage of the technology. More broadly, a gap exists in availability of skilled integration personnel and in financing for public transport authorities to make the transition to these currently expensive buses.

5.2.3 Application introduction for FC forklifts

Fuel cell forklifts were one of the earliest fuel cell applications to be commercialised, in a market niche which values rapid recharge and zero emissions. They fall under the broader category of material handling equipment, which also includes ground support equipment at airports and seaports. Other material handling equipment applications are in the demonstration phase, so the focus in this analysis is on forklifts. PEM is the dominant fuel cell chemistry, with DMFC having found a limited place in the market. The market and the providers are predominantly North American, with Plug Power dominant, using Ballard stacks and increasingly its own in-house models. Nuvera also provides stacks and systems, integrated by Hyster-Yale, its parent company and materials handling vehicle producer. In Europe, H2Logic's activities were taken over by Ballard through Danish subsidiary Dantherm and a collaboration continues with Taiwanese company M-Field. Linde also manufactures FC forklifts, and outside of Europe Toyota has some activities.

[117] Ju Wang, 2016 'Overview of Hydrogen and FCB in China' China Automotive Technology & Research Center http://www.cte.tv/wp-content/uploads/2016/12/5_WangJu_FINAL.pdf

5.2.3.1 FC forklift supply chain description

The forklift supply chain (Figure 12) is identical to other PEM transportation applications up to the application integrator level. In contrast to some other applications, forklifts are not weight constrained due to the need for ballast to offset the front-loaded cargo in typical usage, and often use heavier tanks or even additional ballast. Power levels for forklifts also tend to be smaller than FCEVs or FCEBs, in the 2-20 kW range depending on the type of forklift application, but biased towards the lower power range.

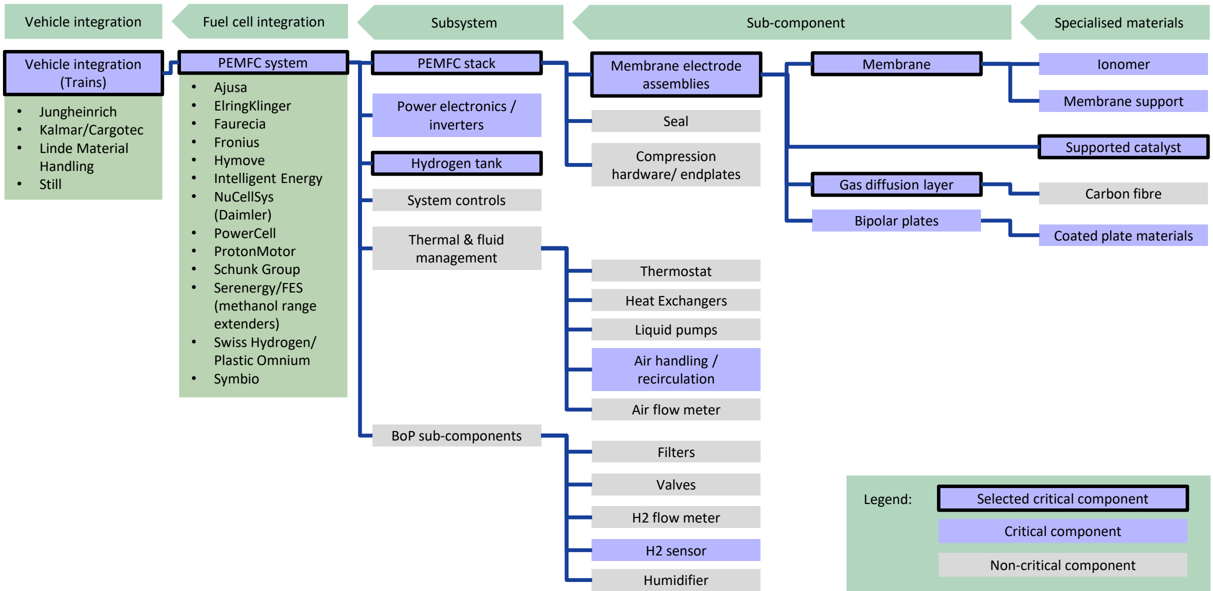


Figure 12: Fuel cells in forklifts supply chain structure with European integrators

As forklifts are a small and specific application, little dedicated KBA activity is present, though skills relevant to other transport systems are very applicable.

5.2.3.2 FC forklift system-level SWOT / gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 43 below shows the results of the SWOT analysis for FC forklifts carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of FC forklifts*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 43: SWOT of European FC forklift supply chain

STRENGTHS	WEAKNESSES
• Some initiatives underway, until now mainly FCHJU • Some local developers and integration capability • Good fuel cell supply base in general for components and subsystems, common to FCEV and FCEB • Major supermarket and other chains who are showing an interest in greening their operations, including through hydrogen[118]	• The stack and to some extent the integrator markets are currently dominated by N American stack suppliers and integrators. This arose because N American markets were more viable, and local suppliers developed capabilities. They are now expanding overseas • Few component suppliers have engaged in this market because of its small size to date, though the capabilities exist • The economics of FC forklifts in the EU have been poor compared to N America (fleet sizes, power prices and other local conditions have a strong influence) • Many different forklift types exist (heavy, light, large, small, extended reach etc). Testing and certifying each one for fuel cells is costly and the market is fragmented • No strong indigenous market leader has helped create demand in the EU • Large fleet owners are typically conservative, so slow to change
OPPORTUNITIES	**THREATS**
• The economics are improving as fuel cell and HRS costs come down, and some large European companies are ordering fleets[119] • Suppliers who have built FCEV and FCEB competences could use these for forklifts • Integration with other supply chains or applications would provide co-benefits (e.g. the forklift refueller could also fuel other trucks in a warehouse). Such 'systems' approaches could help all parties	• Battery forklifts could be improved, especially fast-charging infrastructure and costs, and outcompete fuel cells • Non-EU suppliers may become stronger or continue to dominate the market

The potential exists in Europe for FC forklifts to be produced and deployed, with an important gap in demand related to the comparatively weak economics of the systems. This may require costs to come down before it can be resolved, if novel or integrated business models are not developed. European developers such as Proton Motor have ceased development activities in forklifts, but indigenous capabilities exist should the market evolve.

[118] 'Carrefour Group as new customer for fuel cell forklifts' 2016 http://www.fch.europa.eu/news/carrefour-group-new-customer-fuel-cell-forklifts
[119] 'Colruyt Group invests in hydrogen as a green energy vector' 2016 https://www.colruytgroup.com/en/news/colruyt-group-invests-hydrogen-green-energy-vector

5.2.4 Application introduction for HGVs

In this analysis, heavy goods vehicles or HGVs are those weighing more than 3.5 tonnes, a broader definition than in many instances. This includes both medium duty and heavy duty trucks. Although some specific component sizes and architecture will differ, enough similarity exists to consider them jointly. In Europe, a few trucks have been integrated, including Renault Maxity, Scania and MAN vehicles, the latter modified by ESORO. These are conversions by specialist external integrators, and no truck OEM is currently building vehicles, though some are showing interest. Stacks come from Symbio, from PowerCell and from Hydrogenics. Outside of Europe, Kenworth class 8 trucks have been repowered by Toyota, using Mirai stacks, by US Hybrid, and by Ballard. Nikola Motor is designing and developing its own long-haul unit with stacks from PowerCell in Sweden. Toyota is also working with 7-11 in Japan to provide fuel cell versions of its Hino trucks for local delivery routes.

The supply chain diagram for these applications contains many common components and suppliers, as shown in Figure 9. The HGV chain includes component suppliers shared with other PEMFC applications, dedicated stack and system suppliers as well as established bus makers. For fuel cell dominant architectures, analysis suggests power levels for light-, medium-, and heavy-duty vehicles with a high degree of modularity in early markets.[120] Indeed, modular stacks in the 80-100 kW size range covers the full spectrum of weight classes over the full range of vehicle vocations from urban package delivery vehicles to long-haul trucks. Examples of this strategy include Ballard and Toyota ~100kW stacks used in cars (Toyota), and two ~100 kW stacks being used for buses (both), and HGVs (both).

5.2.4.1 HGV supply chain description

As discussed previously, there is limited specialisation of the critical components among the different transportation applications, though HGV supply chains (Figure 13) are likely to resemble bus supply chains in terms of any specialised components. For example, the membrane may be different from that used in an FCEV, and the bipolar plates may be of graphite not metal. It is reasonable to expect that the application integrator is the main differentiator between FC HGV and other transport applications, at least in the near term.

[120] Brian James, 2018, '2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles' https://www.energy.gov/sites/prod/files/2018/04/f51/fcto_webinarslides_2018_costs_pem_fc_autos_trucks_042518.pdf

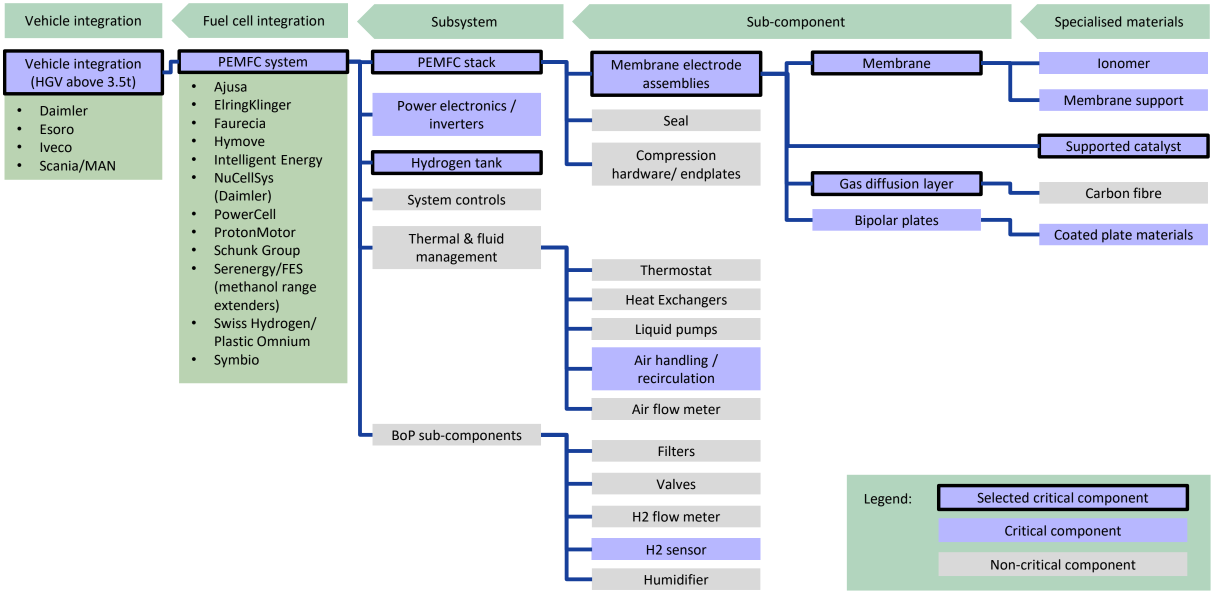


Figure 13: Fuel cells in HGVs supply chain structure with European integrators

HGVs are an emerging area of interest, and while some work has been done in the past, few KBAs focus exclusively on this. Fuel cell waste disposal has been one area with projects including KBAs, but in general the skills applicable to other transport projects are applicable here.

5.2.4.2 HGV system-level SWOT / gap analysis

Table 44 below shows the results of the SWOT analysis for FC HGVs carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of FC HGVs*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 44: SWOT of European FC HGV supply chain

STRENGTHS	WEAKNESSES
• Good supply base, including potential EU stack suppliers and strong automotive component manufacturers, some already working globally on HGV applications • All of the components could be sourced in the EU, though tanks are a bottleneck • Some subcomponent suppliers are globally competitive and components go into non-EU stacks (which may then come back to the EU) • Conditions for FC HGV deployment in the EU are strengthening, with increasing pressure on emissions and increasing interest in greening long-haul truck fleets • Space requirements and refuelling times for FC HGVs cannot be met by batteries	• Stacks from EU suppliers who might supply HGVs have not yet proven long lifetimes, so buyer confidence needs to be developed • Reliance on non-EU companies for much of the tank and its material (specialised C fibre) means costs can be high and supply to other regions is sometimes prioritised • EU-dominated supply chain may not develop, as EU has competition in stack manufacture and tank production may remain more competitive elsewhere • HGV OEMS have developed many different 'clean' options and are low on resources to develop another one

OPPORTUNITIES	THREATS
• Further commitments by supermarkets like Coop and Migros in Switzerland[121] to greener fleets should boost the market • Using tied HGV fleets to help improve HRS economics could enable private vehicles also • Composite material expertise in other industries could be exploited • China's desire to deploy trucks and to build capability offers EU export opportunities • Stack suppliers could enter into JVs with China to demonstrate their lifetime and performance in a market with more demand • Some integrators could supply non-EU regions with current technology, and increase their markets	• Other solutions, e.g. LNG or DME, may delay the market • If costs do not come down, supermarkets and others may not be able to justify fleet budgets • China is developing capabilities rapidly and may be able to supply globally in a few years[122] • Carbon fibre for tanks comes from other regions and supply is short, so higher value markets such as aircraft may continue to be prioritised

Suitable hydrogen storage for heavy, long-distance driving is not yet available (either in Europe or globally). If liquid hydrogen is chosen, liquefaction capacity could become a bottleneck, but this will take some time to materialise. Truck OEMs are not yet fully engaged in FC developments, which is a major gap given the structure of the industry. Some operators are starting to look to non-European manufacturers to ensure development can continue. Further gaps exist in testing and certification capability, and in skilled integrators.

5.2.5 Application introduction for Trains and Light Rail

While the first tests of fuel cells in rail applications were conducted in the early 2000s, only recently have fuel cells become sufficiently mature for the conservative rail industry to consider them more seriously. The most appropriate applications are in light and regional rail, including trams, as very long distance transport requires major fuel storage and refuelling capabilities. A major driver for these applications is decarbonisation policy – diesel trains are heavily polluting and electrification of some lines is an expensive and disruptive infrastructure challenge. Weight and volume constraints are less onerous than for buses and HGVs, but the large amount of fuel required means careful infrastructure and storage development is needed.

In Europe, Germany has taken a lead and regional trains powered by hydrogen fuel cells are now certified for passenger use[123]. The trains are made by Alstom and fuel cell systems come from Hydrogenics. Ballard has also announced a tie-up with Siemens aimed at the same market. The Alstom and Siemens rail businesses have announced a merger, still in process, which would potentially affect this nascent supply chain. One reason for the merger was to compete better against emerging Chinese competition in rail. In fuel cells for rail China is relatively advanced with some light rail and tramway applications entering service, currently also using systems from the Canadian suppliers. The systems are built around existing architecture designed for bus and heavy-duty uses.

[121] https://h2energy.ch/en/major-swiss-companies-push-hydrogen-mobility/
[122] Ju Wang, 2016 'Overview of Hydrogen and FCB in China' China Automotive Technology & Research Center http://www.cte.tv/wp-content/uploads/2016/12/5_WangJu_FINAL.pdf
[123] Alstom Press Release. Available at: https://www.alstom.com/press-releases-news/2018/7/coradia-ilint-hydrogen-train-receives-approval-for-commercial-operation-in-german-railway-networks

5.2.5.1 *Trains and light rail supply chain description*

The rail market is emerging and hence the supply chain is still in development. The strength of Alstom and Siemens position Europe well as integrators, though stacks and systems come from N America.

For primary vehicle power, PEMFC is preferred due to its capacity for rapid power response. The generic supply chain for trains (Figure 14) is very similar to the other PEMFC transport applications discussed. Indeed, Ballard and Hydrogenics have business interests in all of these applications. Furthermore, there is limited specialization of the critical components among the different transportation applications. For example, the membrane for an FCEV might differ modestly from a membrane designed for an FCEB or HGV. These differences, however, are well within the capability of a single supplier. Again, this application is likely to be particularly reliant on high-lifetime FC components, which suggests graphite bipolar plates may be used. The application integrator is however likely to be the main point of divergence in the chain, at least in the near term.

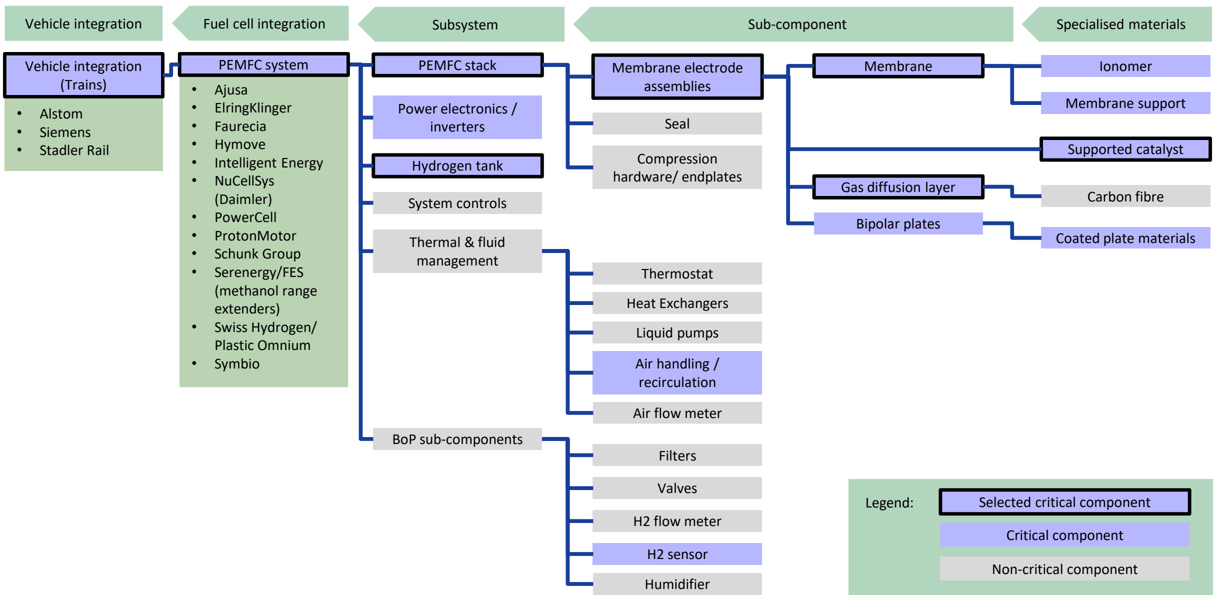


Figure 14: Fuel cells in trains and light rail supply chain structure with European integrators

Some activity has been conducted on both the locomotive and prime mover aspects of FCH rail, and on the infrastructure. Leading KBAs include those with strong existing rail analysis departments, and others who are active in relevant parts of the transport sector.

5.2.5.2 *Trains and light rail system-level SWOT/gap analysis*

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 45 below shows the results of the SWOT analysis for FC rail carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of FC rail*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 45: SWOT of European FC rail supply chain

STRENGTHS	**WEAKNESSES**
• Alstom is one of few global train manufacturers and the only one to have developed a complete FC / hybrid concept to the stage of commercial deployment. Siemens is also strong and engaged • Germany will be the first country to have regional hydrogen trains in public operation which should drive interest and demand in Europe • Some subcomponent suppliers are globally competitive and components go into non-EU stacks (which may then come back to the EU) • Refuelling infrastructure is potentially easier to control and with fewer issues re site space and location (e.g. safety) than for buses, which may be inner-city	• Nascent market (very little operating experience anywhere in the world especially for passenger transport) • Some technical limitations – FC is best suited to relatively short journey distances, though this is a substantial market in Europe • EU-dominated supply chain may not develop, as EU is not leading in stack manufacture and tank production may remain more competitive elsewhere • Rail is a conservative and long-term industry, and limited proof of performance exists for FCH
OPPORTUNITIES	**THREATS**
• Provides viable alternative to electrification with similar performance characteristics (electric drive) and policymakers are starting to voice support (e.g. in the UK) • Strong role in reducing localised air quality problems in e.g. shunting yards • Rail applications may be best suited to liquid hydrogen storage, offering Europe an opportunity to take a global lead	• China is developing capabilities rapidly and may be able to supply globally in a few years, with CRRC looking to expand its reach

A gap exists for European providers of stacks and systems, though some suppliers could develop the capability. Refuelling capability and storage technology more generally require further development. Should liquid hydrogen be considered as an option then Europe's liquefaction capacity would rapidly be reached, and know-how in this area is limited. This application will require time to develop and offers indigenous manufacturers good opportunities in principle, however.

5.2.6 Application introduction for Maritime and Inland Boats

Fuel cells used in maritime and inland boats could help make significant reductions in GHG emissions and to mitigate a significant source of smog producing pollutants near port towns, but factors such as salt in the air and constant movement in multiple planes presents technical challenges. Fuel cells could be applied for both propulsion and hotel loads, but the former is likely only for relatively short journeys (e.g. ferries) in the near term. There have been several shipboard fuel cell power demonstrations, primarily in Europe.[124] PEMFC and SOFC are the primary fuel cell chemistries considered, while MCFC has also been demonstrated but does not appear to be preferred for this application. The two main factors that determine which chemistry is preferred are fuel availability and the ship's operational requirements. Logistics fuels such as diesel are convenient, but

[124] van Biert, L., Godjevac, M., Visser, K., & Aravind, P. V. (2016). A review of fuel cell systems for maritime applications. Journal of Power Sources, 327, 345–364. https://doi.org/10.1016/j.jpowsour.2016.07.007

can have significant impurities which must be removed. Hydrogen, methanol and LNG are available in some locations, and hydrogen is increasingly considered as the long-term choice. The two major operational requirements are trip duration, which affects how sensitive the operation is to energy density, and load response time. Generally, SOFC is more tolerant to impurities but has somewhat slower load response while PEMFC can be poisoned by a number of common fuel impurities and so prefers pure hydrogen, but can respond rapidly to changing loads. One other consideration is the extent to which waste heat can be used on-board, with SOFC providing high quality heat.

Maritime propulsion has been agreed as the focus of this study within the shipping segment. PEMFC is attracting considerable interest linked in part to the potential for air and water quality benefits and reduced CO_2 emissions from low-carbon hydrogen. SOFC and MCFC are not examined here, as their on-board use for hotel loads is very similar to conventional stationary applications which are evaluated in Sections 5.5 and 5.6.

5.2.6.1 Supply chain description

The key differentiator for these applications is the speciality integrator with specific application knowledge. The supply chain (Figure 15) is thus divided in this way.

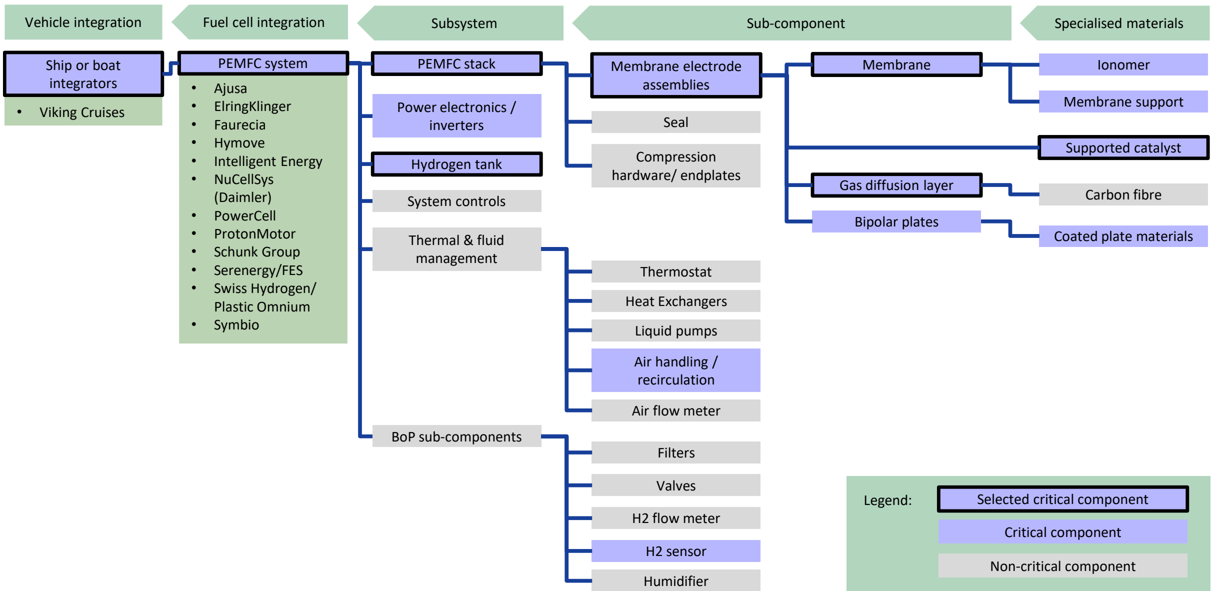


Figure 15: Fuel cells in maritime applications and inland boats supply chain structure with European integrators

Europe has several KBAs with FCH skills specific to the maritime sector, including in the Nordic countries. Others are those with more general FCH system capabilities. Europe is probably marginally stronger than many other regions as this area has been a focus for some time, even though activity has been limited.

5.2.6.2 Maritime and inland boats system-level SWOT / gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 46 below shows the results of the SWOT analysis for maritime FC as a whole, carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of maritime FC*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 46: SWOT of European maritime supply chain

STRENGTHS	WEAKNESSES
• Good supply base, including potential EU stack suppliers and strong component manufacturers • All of the components could be sourced in the EU, except possibly for the on-board storage • Some subcomponent suppliers are globally competitive and components go into non-EU stacks (which may then come back to the EU) • Conditions for marine FC deployment in the EU are improving through regional interest in e.g. Scotland and Norway • Ownership of both vessel and fuelling solution would typically be within one organisation, making optimisation easier	• Very few maritime projects have been conducted so data and confidence are limited • Reliance on non-EU companies for much of the tank and its material (specialised C fibre) means costs can be high and supply to other regions is sometimes prioritised • EU-dominated supply chain may not develop, as EU is not leading in stack manufacture and tank production may remain more competitive elsewhere • System costs are high and hard to reduce, so finding the right financing remains important
OPPORTUNITIES	**THREATS**
• Further commitments by more regions to better air quality could boost the market • Some remote maritime regions have abundant renewable energy and could use it to make hydrogen for local fleets • Integration is a high part of the cost. If it could be optimised, perhaps through support, EU manufacturers could compete better • Composite material expertise in other industries could be exploited	• Regulations may not be strong enough to force technology uptake • If costs do not come down, local authorities may not be able to justify budgets • Carbon fibre for tanks comes from other regions and supply is short, so higher value markets such as aircraft may continue to be prioritised

Very few projects have been realised, and those that have are small-scale, so understanding is still evolving. However, standards and regulations are lacking for maritime applications in particular, and integration capability is a gap globally. Liquefied hydrogen is likely to be required, which would quickly lead to a need for expansion of the European capacity, where gaps exist within the skills base. Incentives for marine operators to develop projects and know-how are also lacking.

5.3 HRS

5.3.1 Application introduction

Hydrogen refuelling stations are integrated from many other systems and components, but unlike many of the other systems discussed they are often bespoke, to allow them to fit into different footprints and under different local regulations, and so the essential part of an HRS is the integration capability. Their key components are often subsystems or technologies (such as storage) which are covered elsewhere in this report. The majority of hydrogen compressors used today are in refuelling systems, for example. In addition to onsite production and storage, some important areas for development include the dispensers and hosing (which is specialised and needs to withstand the very cold hydrogen needed for fast filling), valving and flow meters. The compressor is a major cost component in a refuelling station. Dispensers and controls (including metering) are also important cost factors[125] and product availability for HRS applications is currently low.

5.3.2 Supply chain description

As shown in Figure 16, Europe has several HRS integrators with a global reputation and reach, including Linde, Air Liquide, Nel (H2 Logic) and ITM Power. Europe is also well positioned across most key components in HRS, and some European actors are working on the development of new components (e.g. the dispenser and hosing). There is still a lack of flow meters that meet the accuracy requirements of weights and measures authorities, but there is relevant development activity by some European actors. Other areas, such as in-line purity assurance are still an area of R&D activity, also by component developers. Europe has several hydrogen compressor suppliers to choose from, including some that have developed – or are still developing – novel compression technologies such as electrochemical routes.

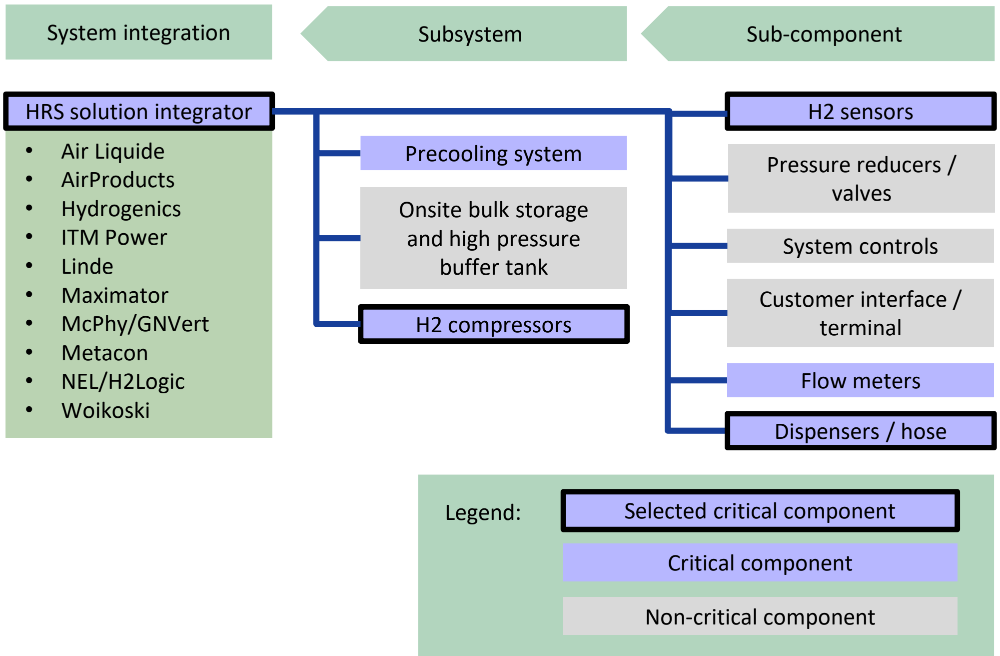


Figure 16: Hydrogen refuelling station supply chain structure with European integrators

As mentioned above, refuelling station activity is primarily focused on integration, and KBAs play a limited role. Some do conduct system modelling and analysis and others have developed skills in monitoring and evaluation, but most more fundamental activity relates to specific components.

5.3.3 Critical components

The critical components for this application are listed in Table 47. There is more detail on the critical components in Section 7.

[125] Argonne National Laboratory - Hydrogen Infrastructure Analysis in Early Markets of FCEVs, IEA Hydrogen Roadmap- North America Workshop 2014. URL: http://www.iea.org/media/workshops/2014/hydrogenroadmap/9anlamgadelgowainy.pdf

Table 47: HRS critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Dispensers / hose	Component	6	7.10
H2 compressors	Sub-system	6	7.5
H2 sensor	Sub-system	6	7.9
HRS solution integration	System	5	5.3
Flow Meters	Component	5	
Precooling	Sub-system	4	

5.3.4 System-level SWOT / gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 48 below shows the results of the SWOT analysis for HRS as a whole carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of HRS*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 48: SWOT of European HRS supply chain

STRENGTHS	WEAKNESSES
• Several strong HRS integrators and suppliers, including small-scale production lines • Expertise in a variety of configurations and scales for liquid and compressed delivery • EU suppliers have delivered HRS worldwide • Good support expertise on safety and standards • Some vertical integration with electrolyser suppliers • Local sourcing for many components, systems and subsystems • Interest is strong, increasingly including fleet vehicles, allowing suppliers to invest in developing their offering	• Current market is small, costs are high, systems are not yet optimised to fit in small spaces • Lack of consensus on technology choice leads to some duplication of effort and fragmentation of approach • Reliability has been poor, so current and future clients may lose confidence • Few suppliers exist for some components, which results in high costs and high supply risks • Having too many different local regulations and standards could hold up deployment and send prospective clients elsewhere • Low utilisation in early years threatens business case, as investors need long-term view

OPPORTUNITIES	THREATS
• Other countries in the EU may become more supportive as vehicles become more widely available, improving the emerging network • Joint market development with fleet providers, utilities or others to maximise benefits could unlock greater potential • Using HRS to also provide local power, grid services or heat could improve economics	• Several N American groups are developing expertise and could compete strongly, and China is starting to do the same • Up-front infrastructure costs may remain too high to allow good competition with BEVs • Different international standards in e.g. Japan, Europe, N America may hold back development • Support for under-utilised infrastructure may diminish or disappear

Europe suffers from the same gaps as other global regions, so is not specifically at a disadvantage. However, successful development and commercialisation of higher performing and lower cost dispensing equipment, hoses, metering equipment and sensors would position Europe well. Other gaps include test capabilities to ensure HRS meet tough standards for refuelling protocols, and a service infrastructure for installed HRS. The availability of reasonably-priced and reliable compressors is a gap here and in other applications

5.4 Micro-CHP

5.4.1 Application introduction

Micro combined heat and power (micro-CHP) units provide both electricity and heat. The electrical output of a micro-CHP ranges from 500 W to 5 kW and is typically used for domestic applications. In Europe, most installed units are between 0.7 kW and 2 kW. Both PEMFC and SOFC are used, though SOFC units are a more common offering in Europe, and increasingly so globally[126].

The European domestic market is developing, helped by support programmes such as the FCHJU's ene.field and PACE projects, and the German KFW433 grant scheme (for systems 0.25-5 kW). However, only a few thousand units are in use, in contrast to installations of around 250,000 in Japan in 2017 alone[127]. There are no other substantial markets for micro-CHP systems.

In contrast to the fuel cell applications previously discussed (FCEV, FCEB, forklift, rail, marine), micro-CHP systems typically operate on hydrocarbon fuels (e.g. natural gas). The fuel may be converted into hydrogen for use by the fuel cell in an on-site reformer or within the fuel cell stack itself (SOFC with internal reforming). The reformer supply chain is considered separately below.

5.4.2 Supply chain description

Micro-CHP PEMFC

There are more **PEM systems** in the micro-CHP sector than in any other stationary power application, and Europe has a long history of development in the area. Europe is strong in many of the components for PEMFC micro-CHP, with a diverse range of actors, some world-leading, but has few actors in final system integration and deployment. The majority of the players are upstream in the supply chain, similar to transport PEM, and includes developers and suppliers of sub-components such as bipolar plates, gas diffusion layers, and catalysts as well as some value added assemblies such as MEAs. Stack developers are starting to produce

[126] Small, M. (2017) 'Overview of ene.field and PACE projects' FCHJU Review Days 2017.
[127] E4tech Fuel Cell Industry Review 2017 http://www.fuelcellindustryreview.com/

commercially viable products, including players working not only on conventional PEM but also high temperature (HT) systems. HT-PEM systems have slightly different characteristics from low temperature ones, and use some different materials – the membrane is typically polybenzimidazole (PBI) and the ion conductor is phosphoric acid contained within it. These HT-PEMs share characteristics with PAFC, but as is common practice, have been included under PEMFC, not PAFC in this report. Europe is strong in HT-PEM and has a lead in this area compared to other regions, from materials through to systems. However, they are so far a minority technology, not only in micro-CHP but generally, and with limited commercial availability. Upstream of the stack the majority of the supply chain is common with non-CHP stationary systems, and greater demand in either sector will help the other.

In stationary PEM systems, upstream materials and stack components are similar to those in transport applications. Dimensions and exact compositions vary, such as changes in catalyst composition to accommodate higher levels of fuel impurities, or thicker membranes for longer lifetimes. Some elements can be made of different materials, such as graphite instead of steel for bipolar plates – the latter typically last less time and may not be used for CHP applications. Systems integration has more possible configurations, as it may include fuel processing and heat exchanger requirements.

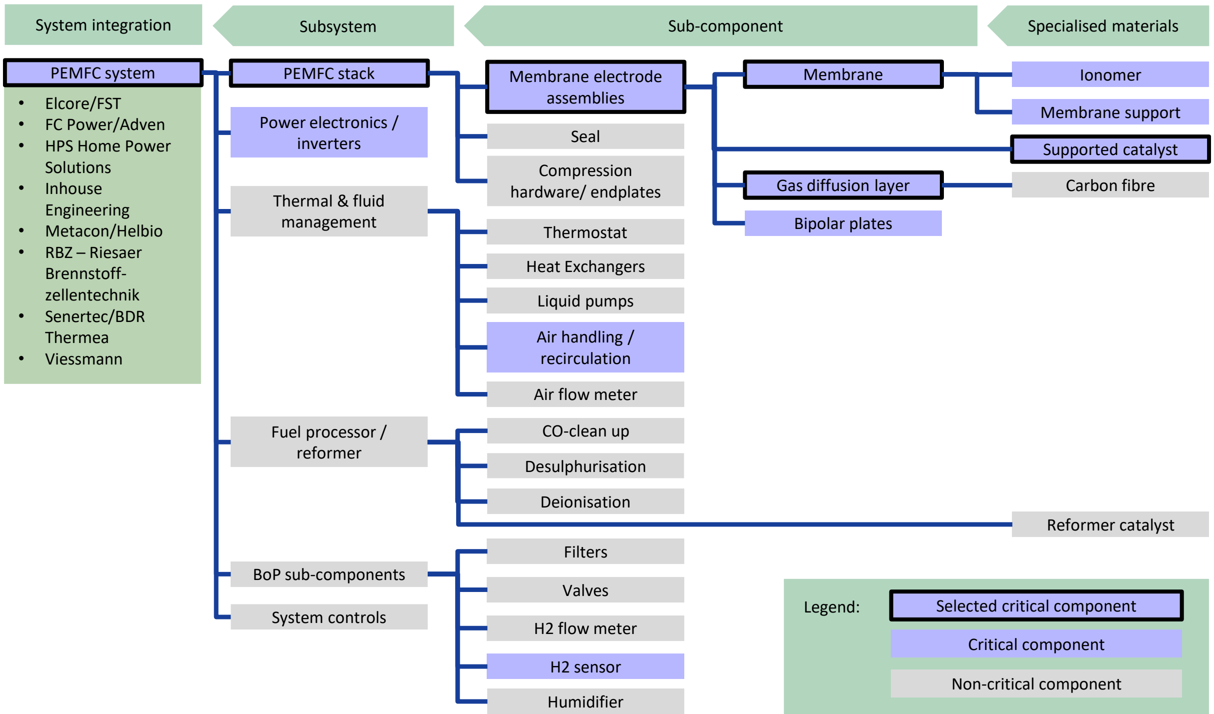


Figure 17: PEMFC micro CHP supply chain structure with European integrators

For SOFC systems the system breakdown is quite similar to that of stationary PEM fuel cells. The selection of critical components again follows the logic of largest cost contributors[128], and seals have been included as critical because of their high specialisation, with only a few suppliers. The stack components and their materials are however very different, suited for much higher temperature operation (above 550°C). CO clean-up is not required for SOFC and so fuel processing is less complex than in PEMFC. The supply chains are shown on separate diagrams, as even at system integrator level, PEMFC and SOFC are rarely interchangeable.

[128] Battelle Memorial Institute, 2016 "Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications" for US Department of Energy https://energy.gov/sites/prod/files/2016/07/f33/fcto_battelle_mfg_cost_analysis_pp_chp_fc_systems.pdf

System integrators who have both PEMFC and SOFC appliances available will have some differentiation in internal technical teams and supply chains.

Europe has strong heating appliance integrators with varied but increasing degrees of participation in fuel cells. Many have a long history in heating appliances (e.g. boiler manufacturers) and in technology integration, but very few have in-house fuel cell stack development. No European player has the depth of experience that is found in Japan, and European PEM stacks and systems are in the early stages of (subsidised) commercial deployment. Some actors have even stopped in-house activity, preferring to source from and partner with the strongest providers globally, who are typically Japanese players (e.g. Panasonic). Although many systems installed in Europe are hence based on imported technology, these are adapted for European conditions and certified locally, with some components also locally sourced. With the exception of Japan, where the Ene-farm programme has led to massive micro-CHP deployment in recent years, Europe, and in particular Germany shows the highest activity internationally, both in terms of breadth of technology suppliers as well as efforts to roll out systems into the market.

Some European companies (e.g. WS Reformer) have developed strengths in reformer technology, and have good capabilities. They already supply systems and know-how for some of the European players, though again Japanese companies have greater experience and have sold many more systems. Reformers are covered in more depth in Section 5.10.

Micro-CHP SOFC

Europe is well-regarded in **SOFC for mCHP**, with several strong players throughout the supply chain. In addition to its own developments, SOLIDpower acquired an established Australian technology with production in Germany, although some components come from other regions, e.g. China. Ceres Power does not yet have a full commercial product but has important partnerships within and outside Europe, which could result in significant export markets in addition to local sales. Other developers are at different stages of progress, including Viessmann, which is embarking on a new iteration of the SOFC system it already has on the market, Bosch and Sunfire which used to supply Vaillant with modules for their paused mCHP product.

Unlike the PEM supply chain, which for micro-CHP is similar to that in transport, the different SOFC system developers typically use different materials sets, manufacturing techniques and stack architectures. Little commonality exists even amongst developers competing in the same markets. Cells may be planar or tubular; ceramic materials can include yttria, ceria, scandia, gadolinia and many more; and stack structures and shapes vary widely. Furthermore, this heterogeneity means that almost no integrators have more than one stack technology, as it becomes inefficient and costly to manage all of the separate components. Many parallel supply chains tend to exist without major interaction. A full assessment of each supply chain would therefore require investigation at an individual company level, which is commercially sensitive, and so the analysis here is partially generic. The level of detail is nevertheless sufficient for the analysis.

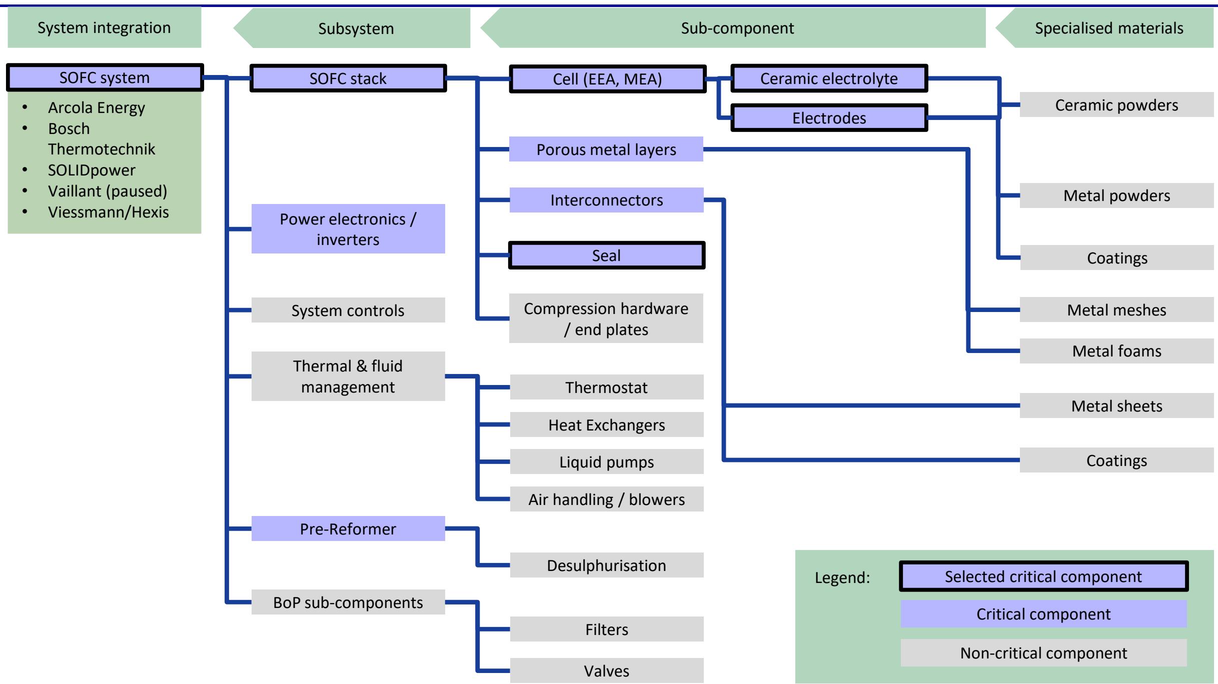


Figure 18: SOFC micro-CHP supply chain structure with European integrators

Another differentiating factor is that SOFC supply chains are also often much more vertically integrated than those for PEM. While some companies buy cells or other stack components and assemble them, others buy powders and carry out the manufacturing process in-house. This is partly because of the difference in SOFC designs discussed above, which makes outsourcing more complex. Although no European system integrator has deployed very large numbers of units (in the tens of thousands), SOLIDpower has deployed close to this through its acquisition of what was CFCL, an early leader in system deployment. In fact globally few players have this experience, with the exception of Kyocera in Japan, who use an uncommon cell design (flattened tubes).

The supply chain is very international. Asian companies supply materials and components globally, and several European companies also supply parts to overseas companies, including in Asia. These could supply stacks or subsystems in the future.

The micro-CHP supply chain has upstream similarities and crossover with larger SOFC systems, at the powders, seals and interconnects level, and to some extent at the cell and stack level. In some cases larger SOFC systems are made from multiple smaller stacks manifolded together, so the supply chains are almost identical. In others the whole stack design is scaled, and this requires different inputs.

Europe has underlying strengths in reformer chemistry, specialist alloys, ceramic powders and cell manufacture and in some areas of stack production, but no company is yet able to fully mass-produce components or systems. This means costs are high, and only national or regional support programmes currently enable sales. The different materials and system architectures make it even more difficult to reach scale. For example, 100 final systems sold in a funded European programme could be of 5 different types, so sales of each component can be much lower.

For SOFC companies that do not do the majority of development and manufacturing in-house, relationships within the conventional micro-CHP sector are often quite close, almost resembling vertical integration. This is a function of the bespoke materials sets and designs required, which means that changing suppliers is even more difficult than for PEM. It also means that the SOFC sector is in many ways more fragile, as companies often depend on other links in the chain where currently only one supplier is engaged.

A range of knowledge-based actors in Europe covers many aspects relevant to mCHP. Those more active in FCHJU projects tend to come from Denmark, Germany, France, Italy, Switzerland and Spain, though strong competence also exists in the UK, and some other countries. European actors have strong skills in system modelling, reactor design, catalysts, cell materials and other areas, on a par with other global regions.

5.4.3 Critical components

The critical components for each FC chemistry associated with this application are included in the tables below. There is more detail on the critical components in Section 7.

Table 49: Micro-CHP PEMFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Supported catalyst	Specialised materials	6	7.14
Membrane	Sub-component	6	7.11
Membrane electrode assemblies	Sub-component	6	7.7
Gas diffusion Layer	Sub-component	6	7.12
PEMFC stack	Sub-System	6	7.2
PEMFC system	System	6	5.4
Membrane support	Specialised materials	4	
Ionomer	Specialised materials	4	
Bipolar plates	Sub-component	5	
Air handling / recirculation	Sub-component	4	
H2 sensor	Sub-component	4	
Power electronics / inverters	Sub-system	4	

Table 50: Micro-CHP SOFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Ceramic electrolytes	Sub-component	6	7.8
Electrodes	Sub-component	6	7.8
Seals	Sub-component	6	7.13
Cell (EEA, MEA)	Sub-component	6	7.8
SOFC stack	Sub-system	6	7.2
Interconnectors	Sub-component	5	
Porous layers	Sub-component	5	
Fuel processors / reformers	Sub-system	5	5.10
SOFC system	System	5	5.4
Power electronics / inverters	Sub-system	4	

5.4.4 System-level SWOT/gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 51 below shows the results of the SWOT analysis for FC mCHP as a whole carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of FC mCHP*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 51: SWOT for European micro-CHP supply chain

STRENGTHS	WEAKNESSES
• Europe has a wide range of integrators and developers with diverse technologies, including some major corporations • Hundreds of units have been deployed, bringing learning from the field[129] • Some European integrators have partnerships with Japanese leaders for EU-specific systems • Europe has a good range of component provision locally and support for developers • Some European technologies and players are very well-regarded. There are some clear technology leaders, especially in SOFC • Germany's support programme for small-scale CHP[130] (0.25 to 5 kW) should help European players develop their markets and subsequently their technologies (though Japanese technology inside local units is also eligible). These subsidies favour smaller systems.	• Japanese companies are an order of magnitude or more ahead in deployment and manufacturing capabilities throughout the supply chain[131] • Japanese components are used by European integrators and Japanese companies could benefit from growth in European market. • Many different designs and materials sets exist, so there is no critical mass for any developer and few common components • Some EU manufacturers are dependent on non-EU supply, e.g. of SOFC powders or cells • Indigenous reformer developers are not at the high development stage of the Japanese • The low power level of micro-CHP systems leads to relatively high prices per kW • Market support has been fragmented between European countries to date and no critical mass of units has been achieved[132] • The wide range of climates and heat/power demands in the EU means standardisation is hard and so cost remains high • The business case for individual units is often poor and so considerable effort is required for sales • Support (e.g. servicing) is not yet well developed

[129] E4tech Fuel Cell Industry Review 2016 http://www.fuelcellindustryreview.com/

[130] The German Federal Ministry for Economic Affairs and Energy (BMWi) has made €150 million available for the period 2016 to 2018 for efficiency measures (Anreizprogramm Energieeffizienz, APEE). Residential CHP fuel cells between 250W and 5kW electric output are supported with an upfront subsidy depending on size. A 1kW mCHP unit is supported with €10,200.

[131] E4tech Fuel Cell Industry Review 2016 http://www.fuelcellindustryreview.com/

[132] FCHJU – "Advancing Europe's energy systems: Stationary fuel cells in distributed generation" 2015 http://www.fch.europa.eu/sites/default/files/FCHJU_FuelCellDistributedGenerationCommercialization_0.pdf

OPPORTUNITIES	THREATS
• Decarbonising heat is a major challenge and these technologies could help[133] • Utilities are trying to find their place in a rapidly-changing energy landscape, and decentralised generation is an option • Linking with housebuilders and other building suppliers to provide the FC as part of the new build package could improve the economics and the overall performance • EU integrators could strengthen overseas links and try to ensure more EU content goes into overseas systems • Manufacturers with potentially competitive options could supply several overseas markets • A robust, low-cost reformer would likely be in strong demand in other regions – the EU has some strengths in this area	• Japanese companies may develop EU-specific systems and compete directly in the EU, instead of partnering • Heating may be done differently – heat pumps for example – so demand may drop • Strong decarbonisation may favour direct hydrogen units or electrical heat pumps over many of the natural gas-fed appliances today, threatening reformer and most SOFC suppliers. • The finances of companies integrating mCHP products may simply not support further development – a huge amount of capital is required to bring costs down to a competitive level

Component availability remains a challenge, but this is hard to address other than with each developer, or through some form of common component specification which in itself requires systems to be very similar. Support and service infrastructures are also nascent. A lower-cost reformer could enable a range of different options.

5.5 Commercial FC prime power and CHP

5.5.1 Application introduction

Commercial FC units are defined in this study as those with electrical output of 5kW to <100kW. In principle SOFC, PAFC, PEMFC and AFC chemistries in this size range are available, but the market is extremely small globally, smaller even than micro-CHP (Section 5.4) and larger primary power and CHP FCs (5.6). This is despite a likely better economic case for commercial-scale than residential micro-CHP, as the capital cost can potentially be better amortised against higher utilisation. From the national perspective, Japan appears most ambitious, looking to build on its lead in the micro-CHP market. The government is proposing to offer similar generous support to small-commercial systems as it does for micro-CHP in the country. There is no such support for stationary units of this size and application in Europe.

5.5.2 Supply chain description

Commercial PEMFC

There are very few PEM commercial FC prime power and CHP integrators either in Europe or globally. The German company RBZ Fuel Cells have developed a small commercial 5kW PEM CHP unit, and Horizon Fuel Cells in China claims a commercial scale offering, but few others. Nevertheless, this area is considered as potentially a stronger market than micro-CHP: the specific cost of the units can be lower because of balance

[133] E4tech 2016 Development of a roadmap for hydrogen and fuel cells in the UK to 2025 and beyond. http://www.e4tech.com/wp-content/uploads/2016/08/HFCroadmap-MainReport.pdf

of plant scale effects; and the business case may be better as more consistent heat and power loads can enable higher utilisation factors.

The structure of the PEM system supply chain upstream of the stack and system integrators for the commercial FC primary power and CHP supply chain looks very similar to that of the other PEMFC stationary and transport applications. Europe is strong in many of the components for PEMFC, which could be applied here. The range of actors is diverse, some world-leading, including actors in bipolar plates, gas diffusion layers, catalysts, and MEAs. Europe is also strong in high temperature PEM systems. However, there is limited activity in the development of this technology, especially for this application. Actors in conventional commercial scale systems have not yet strongly engaged in this area, unlike those active in mCHP.

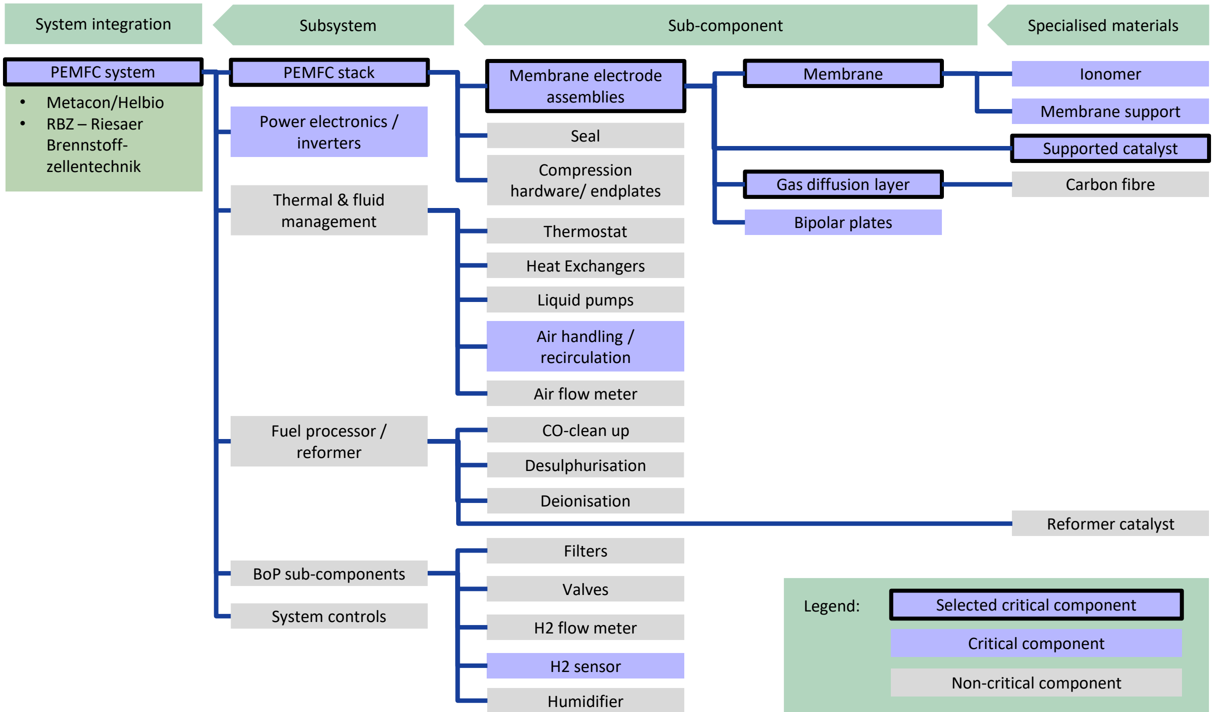


Figure 19: PEMFC commercial FC and CHP supply chain structure with European integrators

Commercial SOFC

A small number of SOFC integrators are focused on commercial FC prime power and CHP in Europe. However, there is not yet demand (or production capability) for these systems globally. Most of the European actors only have systems in a demonstration or early commercialisation phase. SOLIDpower is developing SOFC systems in the 10-60 kW range, as are other European players such as Sunfire, Convion and even some component manufacturers. The units range from 50-300 kW, so the anticipated products are split between the definitions of commercial and large-scale applications for this study. Outside of Europe, Japanese companies Hitachi Zosen and Fuji Electric are trialling 20-50 kW SOFC systems, using Japanese supply chain actors.

The structure of the supply chain upstream of the integrators for commercial primary power and CHP looks similar to that of micro-CHP and large-scale FC and CHP. The fundamental crossover is at the powders, seals and interconnects level, and to some extent at the cell and stack level. In some cases larger SOFC systems are made from multiple smaller stacks manifolded together, so the supply chains are almost identical. In others the whole stack design is scaled, and requires quite different inputs. Like the other stationary applications, the supply chains of a particular SOFC system will vary depending on the specific SOFC type. Again, the heterogeneous designs mean that almost no integrators have more than one stack technology, as it becomes hard to manage all of the separate components. A full assessment of each supply chain would therefore require investigation at an individual company level, which is commercially sensitive, and so the analysis here is partially generic. The level of detail is nevertheless sufficient for the analysis. However, Europe has many strong players in different areas of the supply chain, including powder suppliers, cell and stack manufacturers, specialist ceramic materials and coating companies and high temperature alloy producers.

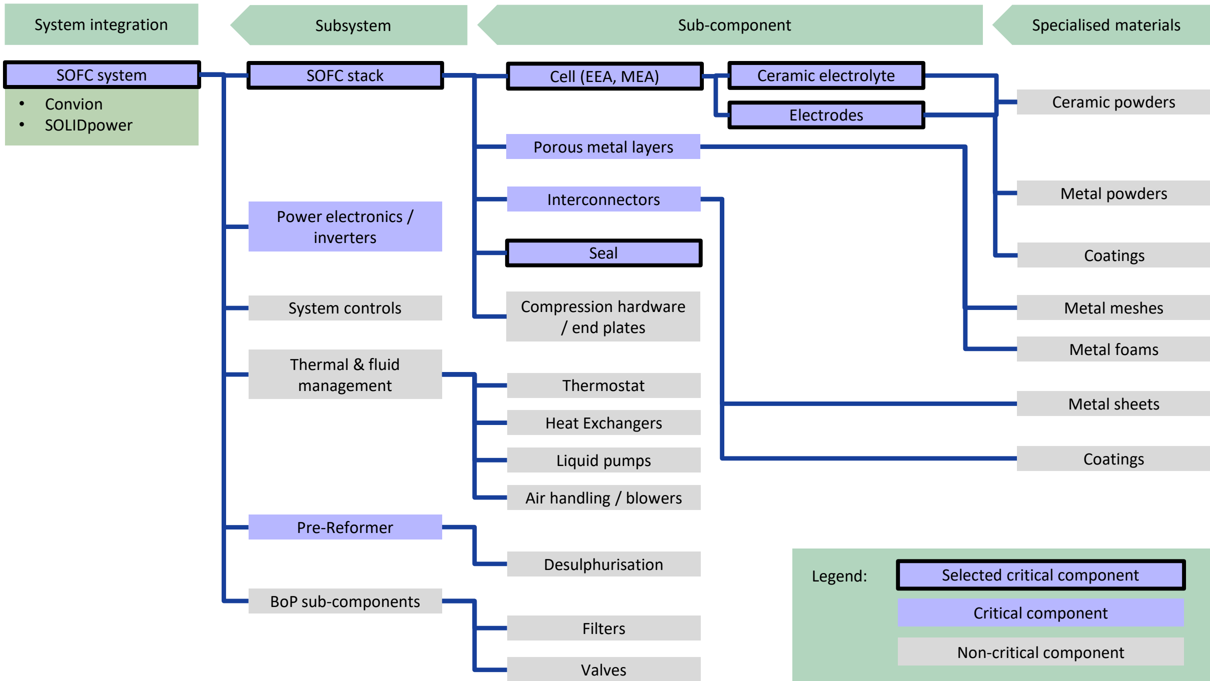


Figure 20: SOFC commercial FC and CHP supply chain structure with European integrator

SOFC supply chains are also often much more vertically integrated than PEMFC. While a few companies buy cells or other stack components and assemble them, many buy powders and carry out the whole manufacturing process in-house. This is because of the difference in SOFC designs discussed above. Similar to the micro-CHP sector, SOFC companies that do not do the majority of development and manufacturing in-house have close relationships within the companies in their supply chain, almost resembling vertical integration. This is a function of the bespoke materials sets and designs required, which mean that changing suppliers is even more difficult than for PEM. It means that the SOFC sector is in many ways more fragile, as companies often depend on other links in the chain where currently only one supplier is engaged.

Commercial PAFC

No PAFC systems are made in Europe, but there is strong European activity in at least one part of the supply chain, namely specialist catalyst supply for the fuel cell itself. The majority of the supply chain is in North America and Korea.

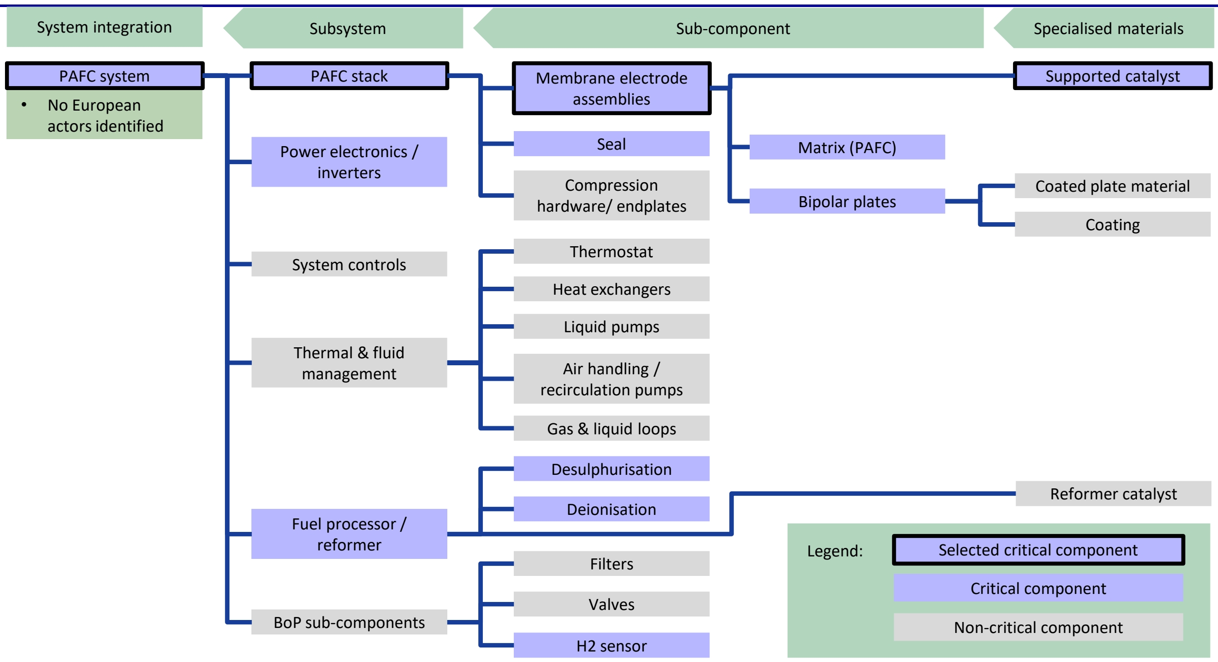


Figure 21: PAFC commercial FC and CHP supply chain structure with European integrator

There are also no European PAFC system or stack integrators; the only two producers globally are Japan's Fuji Electric and Korea's Doosan, which has the capability to integrate systems into buildings and other environments in Europe also, using units manufactured elsewhere. Doosan also has a large manufacturing and development basis in the US, where the technology it acquired was originally developed. Doosan's PAFC systems are industrial scale units (440 kW), while Fuji's 100 kW system just fits into our commercial segment definition.

Commercial AFC

AFC systems are actively developed in Europe at AFC Energy, targeted at large-scale applications. The units are at an early stage and the supply chain is still evolving, but since very few organisations are developing this chemistry the supply chain is somewhat *ad hoc*. Israel's GenCell has commercial units of around 5 kW for sale, but no known work is going on outside Europe. Export opportunities for Europe would mainly be around sales of complete systems to other countries, not of components.

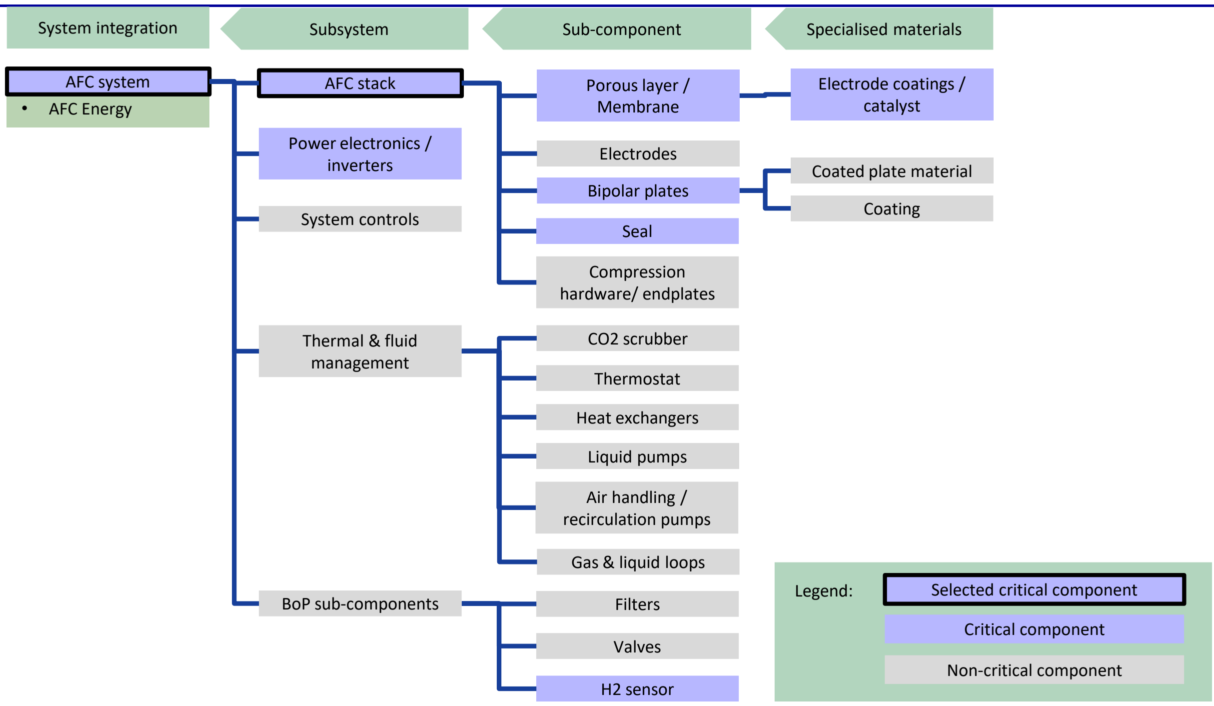


Figure 22: AFC commercial FC and CHP supply chain structure with European integrators

The UK's AFC Energy is currently producing 10 kW modular stacks which build into bigger systems. These are primarily targeted at the large-scale FC primary power market but their modular nature could enable them to take advantage of any future demand for commercial units of 10-100 kW capacity.

While little commercial-scale FC activity is taking place in Europe, European KBAs remain strong in generically useful areas, such as system, thermal and fluid modelling, catalysts and cell and stack components. For SOFC, centres of excellence include Fraunhofer, Imperial College, Riso, EPFL and DLR, and KBAs with expertise in PEM can apply this across the different scales of system. Reformer skills also exist, for example at ZBT in Germany. The level of capabilities in Europe are broadly similar to those found in other leading regions.

Summary

Europe has underlying strengths in reformer chemistry, specialist alloys, ceramic powders and cell manufacture and in some areas of stack production, but very few units have been produced in this 'commercial' size range. Several actors are targeting this market however, typically using developments and sales in micro-CHP as part of their development pathway. Nevertheless, the lack of commercial scale means that costs are high, and different materials and system architectures may have a similar diluting effect on cost reduction as in micro-CHP.

5.5.3 Critical components

The critical components for each FC chemistry associated with this application are included in the tables below. There is more detail on the critical components in Section 7.

Table 52: Commercial FC prime power and CHP PEMFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Supported catalyst	Specialised materials	6	7.14
Membrane	Sub-component	6	7.11
Membrane electrode assemblies	Sub-component	6	7.7
Gas diffusion Layer	Sub-component	6	7.12
PEMFC stack	Sub-System	6	7.2
PEMFC system	System	6	5.5
Membrane support	Specialised materials	4	
Ionomer	Specialised materials	4	
Bipolar plates	Sub-component	5	
Air handling / recirculation	Sub-component	4	
H2 sensor	Sub-component	4	
Power electronics / inverters	Sub-system	4	

Table 53: Commercial FC prime power and CHP SOFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Ceramic electrolytes	Sub-component	6	7.8
Electrodes	Sub-component	6	7.8
Seals	Sub-component	6	7.13
Cell (EEA, MEA)	Sub-component	6	7.8
SOFC stack	Sub-system	6	7.2
Interconnectors	Sub-component	5	
Porous layers	Sub-component	5	
Fuel processors / reformers	Sub-system	5	5.10
SOFC system	System	5	5.5
Power electronics / inverters	Sub-system	4	

Table 54: Commercial FC prime power and CHP PAFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Supported catalyst	Specialised materials	6	7.14
PAFC stack	Sub-system	6	7.2.3
Silicon carbide matrix	Sub-component	5	
Bipolar plates	Sub-component	5	
Seals	Sub-component	5	
PAFC system	System	5	5.5
Desulphurisation	Sub-component	4	
Deionisation	Sub-component	4	
H2 sensor	Sub-component	4	
Power electronics / inverters	Sub-system	4	
Fuel processors / reformers	Sub-system	5	5.10

Table 55: Commercial FC prime power and CHP AFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
AFC stack	Sub-system	6	7.2.2
Electrode coatings / catalyst	Specialised materials	5	
Seals	Sub-component	5	
AFC system	System	5	5.5
Bipolar plates	Sub-component	4	
Hydrogen sensors	Sub-component	4	
Porous layer / membrane	Sub-component	4	
Power electronics / inverters	Sub-system	4	

5.5.4 System-level SWOT/gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 56 below shows the results of the SWOT analysis for FC prime power and CHP as a whole carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of FC prime power and CHP*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 56: SWOT for European Commercial FC prime power and CHP supply chain

STRENGTHS	WEAKNESSES
• Europe has a good range of component provision locally and support for developers • Existing players are developing options in this space, especially in SOFC • Europe has strong supply chain actors in some specific technologies, for example European catalyst manufacturers supply to non-European companies	• Market for commercial prime power FC and CHP in Europe has not started to be developed • Little or no market support currently exists for this size of unit • This limited activity means that few players in the supply chain are targeting these markets • The commercialisation level of the EU technology is not high; mainly demonstrations at different levels • The industry is fragmented, and may not have easy access to the funds required to scale up production and thus reduce cost • Many different designs and materials sets exist, so there is no critical mass for any developer and few common components • Some EU manufacturers are dependent on non-EU supply, e.g. of SOFC powders or cells • The wide range of climates and heat/power demands in the EU means standardisation is hard and so cost risks remaining high • Support (e.g. servicing) is not yet well developed

OPPORTUNITIES	THREATS
• Currently no region is leading globally in this application, giving European suppliers a chance to fill this gap • Decarbonising heat is a major challenge and FC could help[134] • Utilities are trying to find their place in a rapidly-changing energy landscape, and decentralised generation is an option • Developing partnerships with commercial building suppliers to provide the FC as part of the new build package could improve the economics and the overall performance • Linking power-only solutions to autonomous renewable solutions or waste hydrogen streams could help the economics • EU integrators could strengthen overseas links and try to ensure more EU content goes into overseas systems • Manufacturers with competitive options could supply several overseas markets • A robust, low-cost reformer would likely be in strong demand in other regions – the EU has some strengths in this area	• Other regional markets are leading in the areas of both mCHP and large FCs. This intermediate category could be filled by developed supply chains for the technology but for increased or decreased scale for the commercial market. • Heating may be done differently – heat pumps for example – so demand may drop • Other generating technologies may come to dominate markets • Strong decarbonisation may favour direct hydrogen units or electrical heat pumps over many of the natural gas-fed appliances today, threatening reformer and most SOFC suppliers. • The finances of companies integrating these FC products may simply not support further development – a huge amount of capital is required to bring costs down to a competitive level

While this space seems to offer a potentially promising market opportunity, no support schemes currently target it, other than demonstrations such as the FCH JU DEMOSOFC and ComSos projects. A suitable mechanism could significantly help develop this market. The supply chain is not established, though the main gaps are in the FC-specific components as conventional balance of plant becomes easier to source in these size ranges. Servicing and other customer support would need to be developed, but is not yet required.

5.6 Large FC primary power and CHP

5.6.1 Application introduction

Large primary power or large CHP FCs are defined here as those with an electrical output of more than 100 kW. Almost all chemistries are used in this application: PEMFC, SOFC, MCFC, PAFC and AFC.

The market for large FC CHP and primary power in Europe has been slow to develop as few support schemes exist, and almost all installations are in Asia and the US. Korea accounts for a large proportion of the global market, targeting primary power FCs to fulfil renewables obligations and meet co-generation requirements for new buildings[135], while in the US installations benefit from federal Investment Tax Credits and local state-based subsidies. A handful of units have been installed in Europe.

[134] E4tech 2016 Development of a roadmap for hydrogen and fuel cells in the UK to 2025 and beyond. http://www.e4tech.com/wp-content/uploads/2016/08/HFCroadmap-MainReport.pdf
[135] E4tech Fuel Cell Industry Review 2017 http://www.fuelcellindustryreview.com/

5.6.2 Supply chain description

Large-scale PEMFC

The few existing large-scale PEM systems usually use by-product hydrogen to produce primary power, though CHP configuration is possible in principle. The supply chain (Figure 23) is similar to other PEM supply chains at the upstream end, e.g. for GDLs and catalysts, and large-scale systems are usually made from many smaller stacks integrated together. Europe has good capabilities throughout, in principle, but these have not been strongly tested, as very few large scale PEM units have been built. As a consequence, integrators often work on an *ad hoc* basis rather than with repeat designs, although the skills and capabilities for product integration have been proven. Weaknesses in this area stem mainly from the lack of deployed units, so very few data are available and standardisation and cost reduction are hard to achieve.

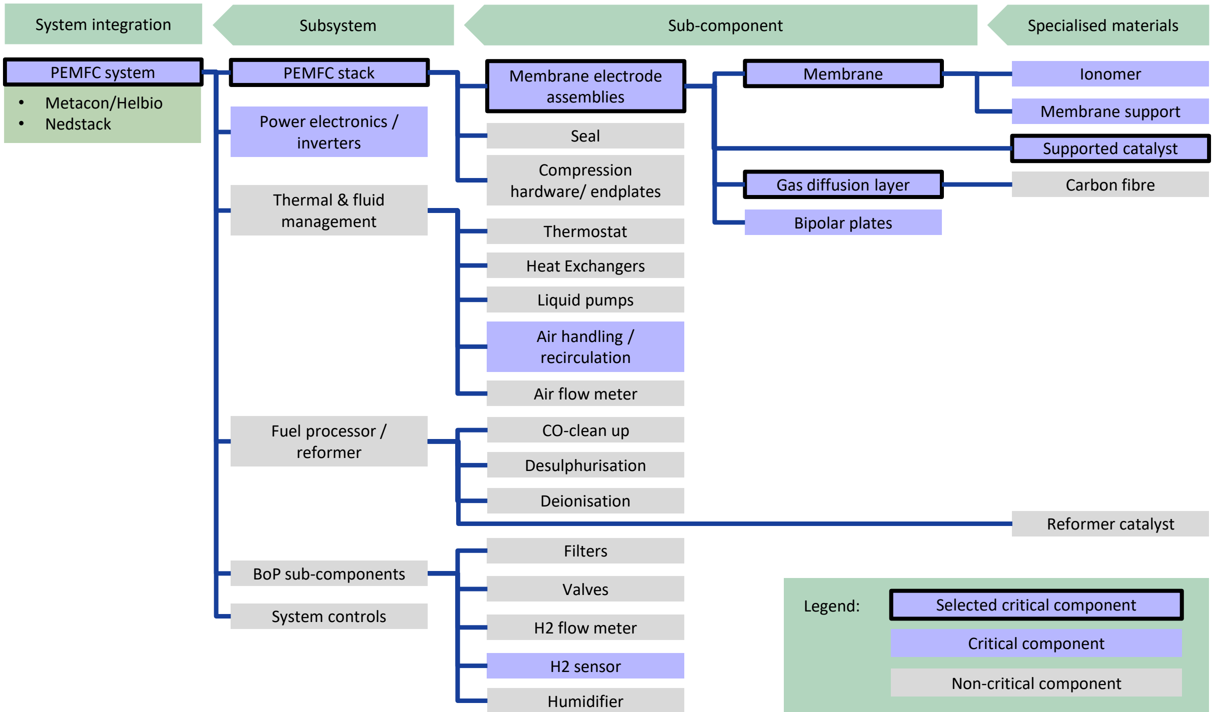


Figure 23: PEMFC large FC CHP and primary power supply chain structure with European integrators

European **large PEM** has thus far only been deployed by Nedstack in China, using a general engineering firm as system integrator as part of the FCH JU project DEMCOPEM-2MW. It requires some further development and optimisation before it is fully commercial. Whilst CHP is an option for these plants, in practice they are likely to operate in power-only mode unless a suitable local heat requirement exists. This affects the economics both because less of the input energy can be used, but also because the non-CHP system is lower cost.

Large-scale SOFC

Few large-scale SOFC systems have been made or deployed other than by Bloom Energy, mainly in the US, though several companies are targeting this area. Designs vary substantially between the different players and so once again each supply chain for different SOFC designs can be quite different. Stack and system developers often make their own ceramic components and assemble stacks and systems in-house. There is some commonality with the SOFC mCHP supply chain, including some developers who do both, but overall the supply chain (Figure 24) is fragile because of this limited number of players, all with different approaches. This means that many components for a given system are only supplied by one company.

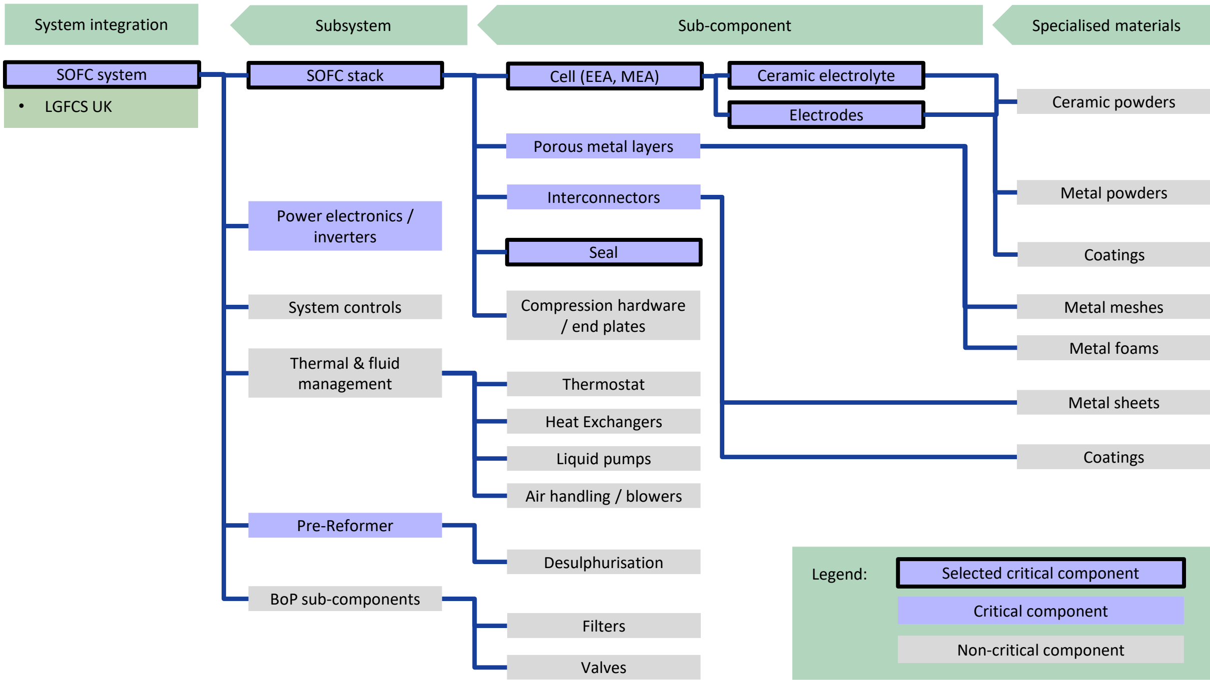


Figure 24: SOFC large FC CHP and primary power supply chain structure with European integrators

Finland's Convion is developing SOFC technology that can be used in a CHP configuration. Units vary in size between 50 and 300 kW. There are no other European system integrators in large-scale SOFC, though LG Fuel Cells is aiming to produce power-only 1 MW hybrid systems and has facilities in the UK in addition to the US and Korea.

Large scale MCFC

Europe plays a generally small role in larger systems outside of PEMFC and SOFC. In MCFC there has historically been some academic research and some corporate development of systems but this has not been continued. European representation for FuelCell Energy is through a European-US venture, FuelCell Energy Solutions, with some in-house development and production capability. The majority of the supply chain (Figure 25) is overseas, in North America and Korea.

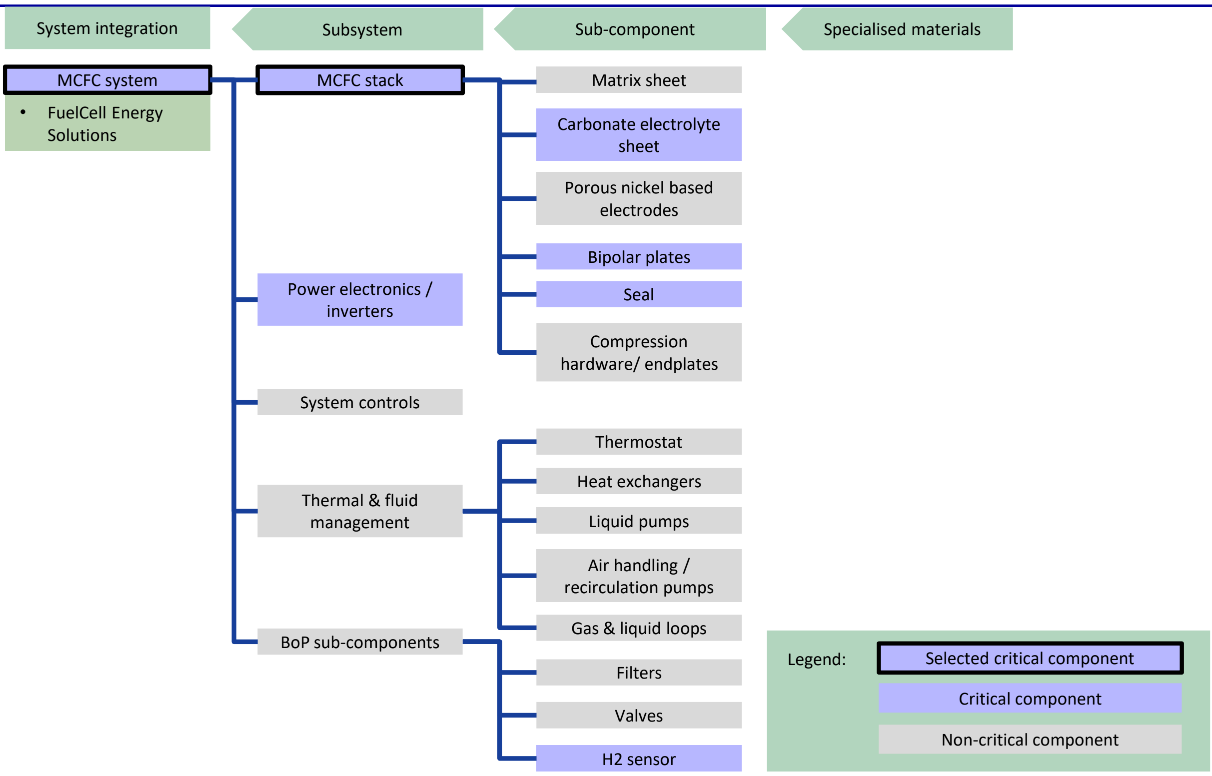


Figure 25: MCFC large FC CHP and primary power supply chain structure with European integrators

Large-scale PAFC

In PAFC systems there is strong European activity in at least one part of the supply chain, that of specialist catalyst supply, but again the majority of the supply chain (Figure 26) is in North America and Korea.

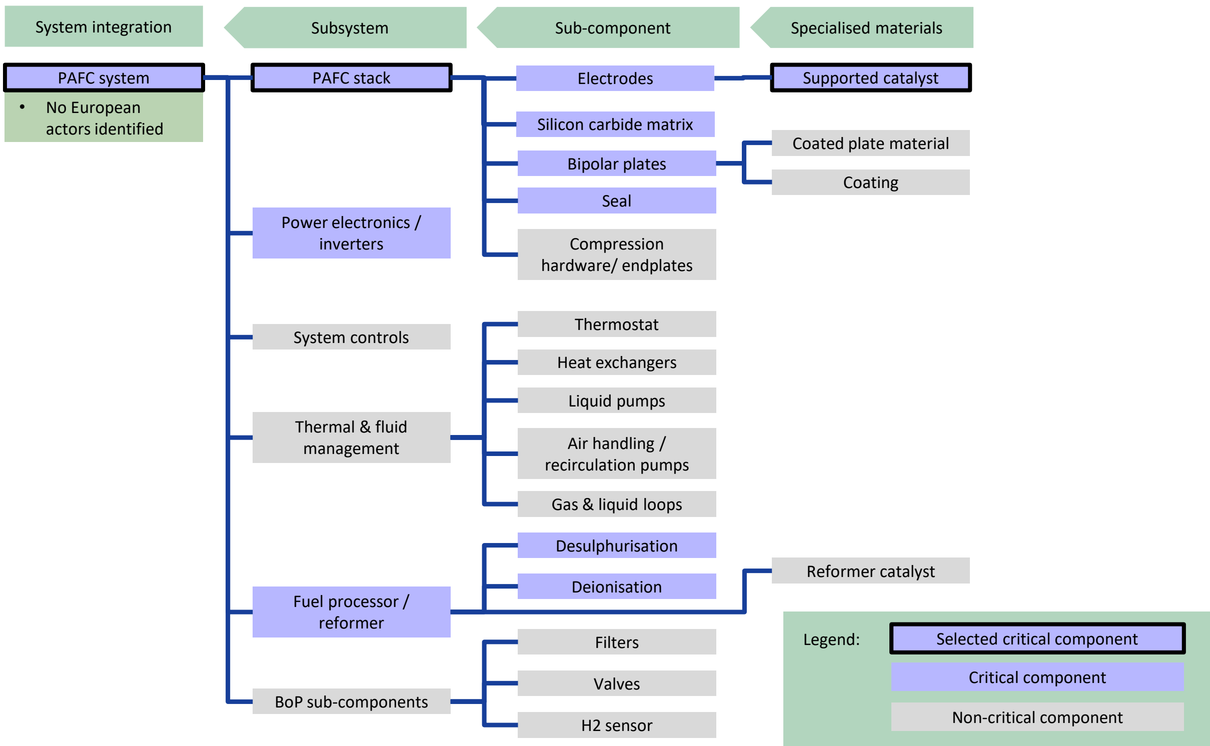


Figure 26: PAFC large FC CHP and primary power supply chain structure with European integrators

PAFCs are currently only produced by two companies: Fuji Electric and Doosan. The latter has a factory in Korea, which combined with its current production capacity in the US has allowed global PAFC shipments to grow to more than 80 MW in 2017. The main market for these systems remains utility-scale power generation in Korea. However, Fuji Electric, together with its German branch Fuji N2telligence, is increasingly targeting a special market where their product acts as active fire prevention – by reducing available oxygen and simultaneously generating power[136].

Large-scale AFC

AFC systems are actively developed in Europe, targeted at large-scale deployment. The units are at an early stage and the supply chain (Figure 27) is still evolving, but since very few organisations are developing this chemistry the supply chain is very *ad hoc*. Little work is going on outside Europe, so export opportunities would mainly be around sales of complete systems to other countries, not components.

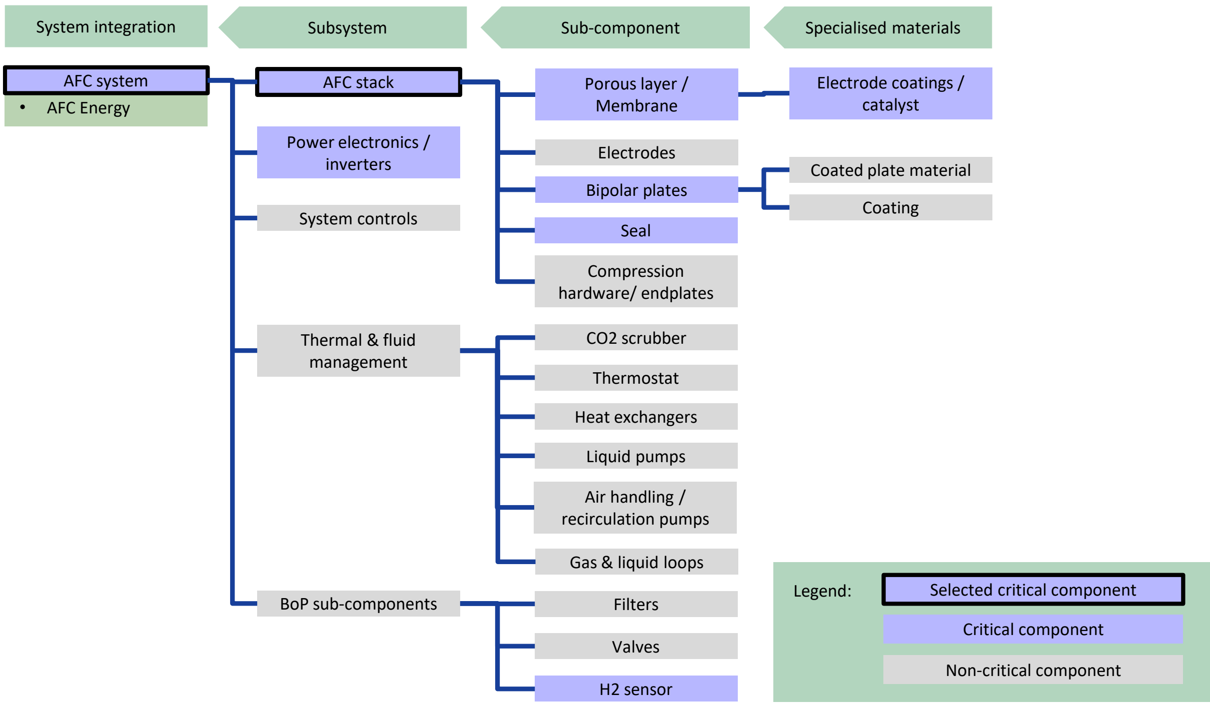


Figure 27: AFC large FC CHP and primary power supply chain structure with European integrators

The UK's AFC Energy is Europe's only actor in this FC chemistry, developing technology for large-scale applications in part through EU-funded projects. GenCell, from Israel, has AFC technology commercially available but in a smaller size range.

Work on large FC systems has also declined in Europe, though KBAs linked for example to LG (Rolls-Royce) remain active. Again, many of the skills demonstrated by the KBAs are applicable quite broadly, and include system optimisation, engineering component design, cell and stack technology integration and catalysis. In this area Europe's capabilities are strong but regions with more commercial activity (Japan, Korea, North America) are likely to be stronger, simply due to the ongoing industrial development and interaction.

[136] E4tech Fuel Cell Industry Review 2017 http://www.fuelcellindustryreview.com/

Summary

Europe has limited product development in large-scale CHP more broadly. AFC Energy is building final systems, much like Nedstack, but these are at demonstration stage and not yet mass produced. Again, they have an almost completely different materials and component supply chain from other fuel cell types. FuelCell Energy is primarily engineering systems produced in the US, but also has some integration capacity in Europe, and Doosan Babcock uses units from its parent company Doosan, which have largely US and Korean technology, though the catalyst supply is European. Europe has good engineering firms capable of putting these systems together and some deploy outside Europe, but the markets to date have been very small.

5.6.3 Critical components

The critical components for each FC chemistry associated with this application are included in the tables below. There is more detail on the critical components in Section 7.

Table 57: Large FC prime power and CHP PEMFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Supported catalyst	Specialised materials	6	7.14
Membrane	Sub-component	6	7.11
Membrane electrode assemblies	Sub-component	6	7.7
Gas diffusion Layer	Sub-component	6	7.12
PEMFC stack	Sub-System	6	7.2
PEMFC system	System	6	5.6
Membrane support	Specialised materials	4	
Ionomer	Specialised materials	4	
Bipolar plates	Sub-component	5	
Air handling / recirculation	Sub-component	4	
H2 sensor	Sub-component	4	
Power electronics / inverters	Sub-system	4	

Table 58: Large FC prime power and CHP SOFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Ceramic electrolytes	Sub-component	6	7.8
Electrodes	Sub-component	6	7.8
Seals	Sub-component	6	7.13
Cell (EEA, MEA)	Sub-component	6	7.8
SOFC stack	Sub-system	6	7.2
Interconnectors	Sub-component	5	
Porous layers	Sub-component	5	
Fuel processors / reformers	Sub-system	5	5.10
SOFC system	System	5	5.6
Power electronics / inverters	Sub-system	4	

Table 59: Large FC prime power and CHP MCFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
MCFC stack	Sub-system	6	7.2.4
Seals	Sub-component	5	
Carbonate electrolyte sheet	Sub-component	5	
Bipolar plates	Sub-component	5	
MCFC system	System	5	5.6
H2 sensors	Sub-component	4	
Power electronics / inverters	Sub-system	4	

Table 60: Large FC prime power and CHP PAFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Supported catalyst	Specialised materials	6	7.14
PAFC stack	Sub-system	6	7.2.3
Silicon carbide matrix	Sub-component	5	
Bipolar plates	Sub-component	5	
Seals	Sub-component	5	
PAFC system	System	5	5.6
Desulphurisation	Sub-component	4	
Deionisation	Sub-component	4	
H2 sensor	Sub-component	4	
Power electronics / inverters	Sub-system	4	
Fuel processors / reformers	Sub-system	5	5.10

Table 61: Large FC prime power and CHP AFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
AFC stack	Sub-system	6	7.2.2
Electrode coatings / catalyst	Specialised materials	5	
Seals	Sub-component	5	
AFC system	System	5	5.6
Bipolar plates	Sub-component	4	
Hydrogen sensors	Sub-component	4	
Porous layer / membrane	Sub-component	4	
Power electronics / inverters	Sub-system	4	

5.6.4 System-level SWOT/gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 62 below shows the results of the SWOT analysis for FC prime power and CHP as a whole carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of FC prime power and CHP*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 62: SWOT for European Large FC primary power and CHP supply chain

STRENGTHS	WEAKNESSES
• Some pure-play companies with potentially competitive technologies exist • Some proven strong integrators are present, and other engineering companies have similar skills which could be exploited • Europe has a diversity of technology types, a few with primarily local supply chains, though these are typically the less mature technologies • Europe has strong supply chain actors in some specific technologies, for example European catalyst manufacturers supply to non-European companies	• There is very limited activity throughout Europe – only a few units are in service[137] • This limited activity means that few players in the supply chain are targeting these markets • The commercialisation level of the EU technology is not high; mainly demonstrations at different levels • So far the markets targeted have proven hard to access, with limited support • High capital costs are proving hard to bring down, slowing market development • The industry is fragmented, and may not have easy access to the funds required to scale up production and thus reduce cost
OPPORTUNITIES	**THREATS**
• Decarbonising heat is a major challenge and this could be one approach to help • Utilities are trying to find their place in a rapidly-changing energy landscape, and decentralised generation is an option • Linking with commercial building suppliers to provide the FC as part of the new build package could improve the economics and the overall performance • Linking power-only solutions to autonomous renewable solutions or waste hydrogen streams could help the economics • China and other non-European markets with favourable conditions could be an interesting market for EU companies, as shown by Nedstack's demonstration plant in China [138]	• Developments in N America and Asia are better-supported by governments. The companies exploiting the opportunities tend to be larger and more able to fund developments[139]. As EU markets emerge, these overseas companies may simply supply into the EU through local partners • Other generating technologies may come to dominate markets

Few indigenous players have strength in this market, so gaps exist both at a technology and supplier level. This has knock-on effects through the supply chain but would be hard to address without a comprehensive programme.

[137] E4tech Fuel Cell Industry Review 2016 http://www.fuelcellindustryreview.com/
[138] "Launching Ceremony in China of the World's first 2MW PEM fuel cell power plant" 2016 http://www.demcopem-2mw.eu/worlds-first-2mw-pem-fuel-cell-power-plant/
[139] E4tech Fuel Cell Industry Review 2016 http://www.fuelcellindustryreview.com/

5.7 Back-up power and gensets

5.7.1 Application introduction

Fuel cell systems used for emergency and off-grid power are in many cases commercially available and generally have a capacity up to 10 kW[140]. This application is often used for telecoms systems and end-uses that require an uninterruptable power supply (UPS). The majority of such systems are PEMFC and DMFC, though AFC plays a small role, and a few specialised SOFC systems are also deployed, though not in Europe or produced by European companies. One industrial actor, SFC Energy, produces DMFC systems for this application, for example for military and recreational customers. They are differentiated from other stationary systems because they run intermittently, requiring different system configurations, lifetime and durability. Only PEMFC is assessed here, as the other chemistries have an extremely minor role.

There are small but growing markets for FC back-up power and gensets in North America and Asia in particular, and for specialist systems such as emergency services grid networks in Europe. Countries with particularly unreliable grid connections or areas without grid connection may offer the best business cases for back-up or off-grid systems. Therefore, this favours sales in developing and emerging markets. The market in Europe is not as attractive, partly because of the generally good reliability and coverage of the electricity grid networks in European countries. Nonetheless, there are ongoing demonstration activities in Europe such as for instance the FCH 2 JU project EVERYWH2ERE using FC as gensets in temporary applications.

5.7.2 Supply chain description

Back-up and genset PEMFC and DMFC

The structure of the PEMFC and DMFC system supply chain upstream of the stack and system integrators is similar to the other stationary applications. Europe is strong in many of the components for PEMFC and DMFC, with a diverse range of actors, some world-leading, including actors in bipolar plates, gas diffusion layers, catalysts and MEAs. In PEMFC, Proton Motor in Germany supplies systems into this market, as has FutureE using Canadian stack technology, while EPS of Italy also has such units, including fully autonomous systems that incorporate an electrolyser. As indicated on the supply chain diagram (Figure 34), several other system integrators either have a commercial PEMFC system for back-up power and gensets or are developing one.

[140] US DoE 2014 Early Markets: Fuel Cells for Backup Power
https://www.energy.gov/sites/prod/files/2014/10/f19/ftco_early_mkts_fc_backup_power_fact_sheet.pdf

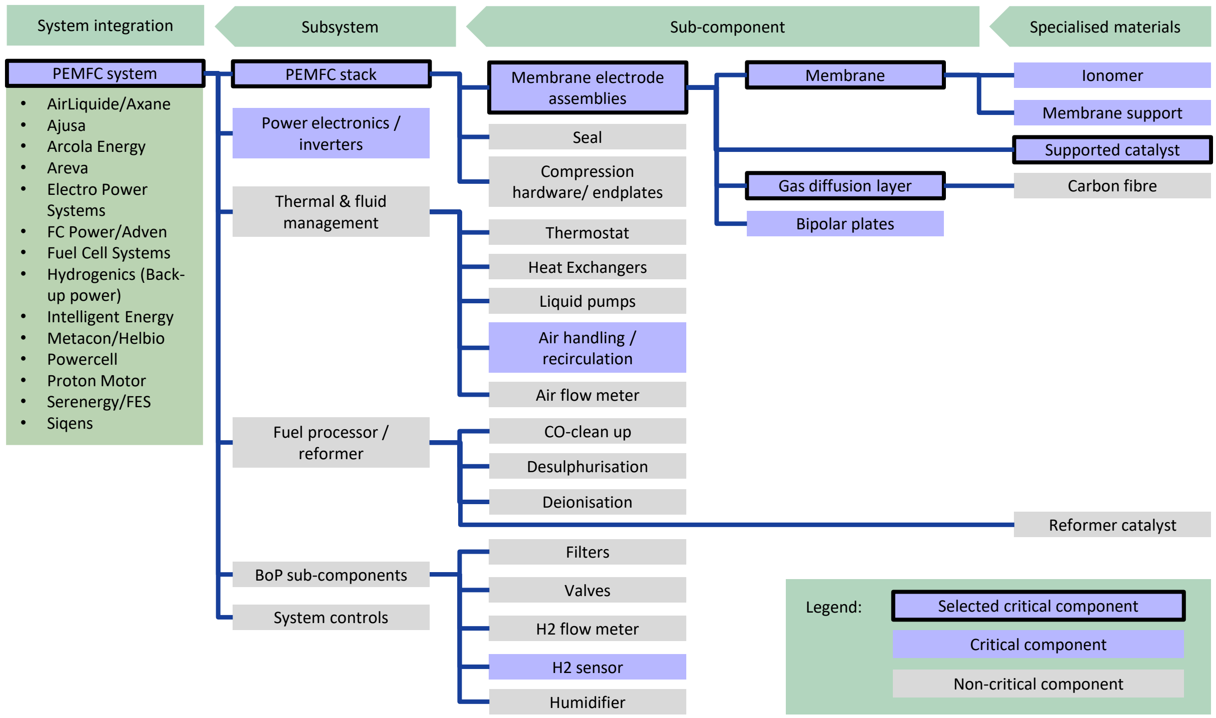


Figure 28: PEMFC back-up power and genset supply chain structure with European integrators

Outside of Europe, M-Power in Taiwan, Plug Power and Altergy of the US, Hydrogenics in Canada, and other companies supply PEMFC technology into this market. Horizon Fuel Cells also supplies PEM back-up systems to many sites in Asia.

DMFC components are mostly similar to PEMFC, but only SFC Energy integrates such systems and stacks, selling them into applications ranging from military to recreational (Figure 29).

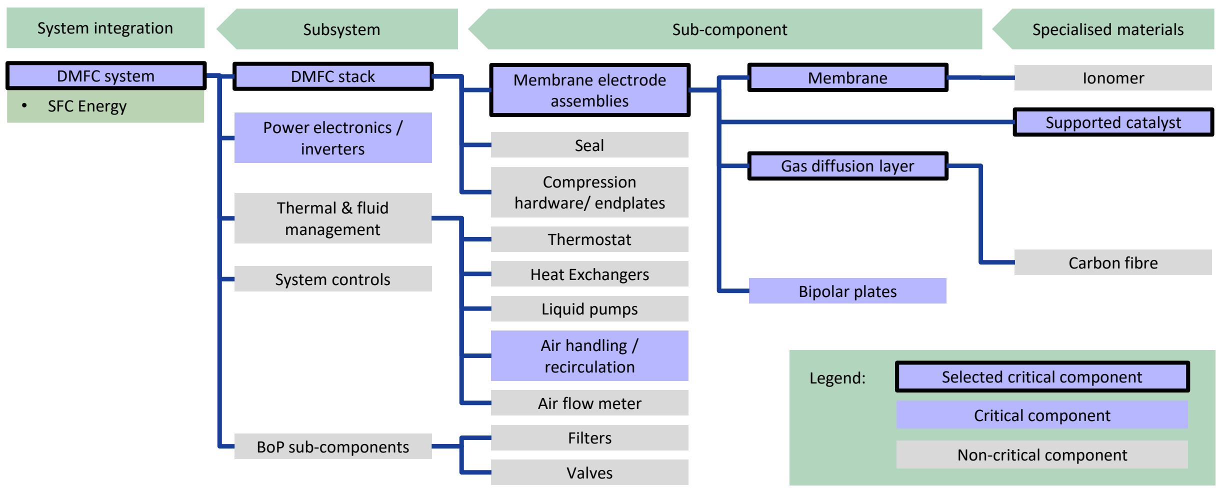


Figure 29: DMFC back-up power and genset supply chain structure with European integrators

As with other stationary applications, European KBAs have a wide range of relevant capabilities in these applications. Some KBAs have also ventured into this area from a preliminary commercial perspective, looking to supply small stacks or systems or spin out companies. As for other stationary systems, skillsets include stack and system design and optimisation, including cell-level modelling and also from an electrochemical, fluid flow, thermal and other perspective. These skills are at least on a par to those in other parts of the world, with some individual institutions globally recognised (CEA, ZBT, DLR, PSI and many others).

5.7.3 Critical components

The critical components for PEMFC associated with this application, and for DMFC are included in the tables below. Because of the very limited European activity in SOFC and AFC in this area, they are not considered. There is more detail on the critical components in Section 7.

Table 63: Back-up power and genset PEMFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Supported catalyst	Specialised materials	6	7.14
Membrane	Sub-component	6	7.11
Membrane electrode assemblies	Sub-component	6	7.7
Gas diffusion Layer	Sub-component	6	7.12
PEMFC stack	Sub-System	6	7.2
PEMFC system	System	6	5.7
Membrane support	Specialised materials	4	
Ionomer	Specialised materials	4	
Bipolar plates	Sub-component	5	
Air handling / recirculation	Sub-component	4	
H2 sensor	Sub-component	4	
Power electronics / inverters	Sub-system	4	

Table 64: Back-up power and genset DMFC critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Supported catalyst	Specialised materials	6	7.14
Membrane	Sub-component	6	7.11
Membrane electrode assemblies	Sub-component	6	7.7
Gas diffusion Layer	Sub-component	6	7.12
DMFC stack	Sub-System	6	7.2
DMFC system	System	5	5.7
Bipolar plates	Sub-component	5	
Air handling / recirculation	Sub-component	4	
Power electronics / inverters	Sub-system	4	

5.7.4 System-level SWOT/gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 65 below shows the results of the SWOT analysis for FC backup power and gensets carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of FC backup power and gensets*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 65: SWOT for European FC backup power and gensets supply chain

STRENGTHS	WEAKNESSES
• Some pure-play companies with potentially competitive technologies exist • Some proven strong integrators are present, and other engineering companies have similar skills which could be exploited • Europe has a diversity of technology types, a few with primarily local supply chains, though these are typically the less mature technologies • Europe has strong supply chain actors in a wide range of specific technologies, including bipolar plates, MEAs, catalysts etc	• The market is tough, with conservative buyers who need to be persuaded of the benefits, and in complex environments such as parts of Asia and Africa[141]. • There is limited market deployment within Europe • This limited activity means that few players in the supply chain are targeting these markets • The commercialisation level of the EU technology is not high; mainly demonstrations at different levels • So far the markets targeted have proven hard to access, given limited support • High capital costs are proving hard to bring down, slowing market development
OPPORTUNITIES	**THREATS**
• Export potential exists for superior products to large markets in Asia, Africa, North America and others. • Reducing noise and pollution in UPS and emergency back-up whilst improving performance would be welcomed by some markets, and be more compelling once proven and at low cost. • Demonstration through linking with European companies with UPS and off-grid needs could be an example to countries with resistance to using FCs for this service • Little development is going on outside Europe, so export opportunities would mainly be around sales of complete systems to other countries, not specifically components.	• Already established global players in this application e.g. Ballard, Plug Power are already in the larger markets and could expand into others. • Other storage or generating technologies may come to dominate markets, for instance, PV and battery systems.

This market is driven by both cost and reliability and so the most important gaps relate to these issues. Volumes remain small so costs are high, but will be driven down as other applications commercialise. No high-profile technology gaps exist. Fuel provision for some operations and locations is a problem, both in terms of availability and quality. Few qualified servicing staff are available.

5.8 Electrolysers

5.8.1 Application introduction

Electrolysis is commercially mature, and has been used in industrial applications for many decades. These applications are relatively undemanding in terms of dynamic response, footprint and power density and have

[141] E4tech Fuel Cell Industry Review 2017 http://www.fuelcellindustryreview.com/

often been able to bear relatively high hydrogen prices. FCH applications have quite different requirements, being usually cost-sensitive in addition to potentially requiring very dynamic duty cycles. Specific applications under development or consideration include on-site hydrogen production for HRS; using hydrogen from electricity for energy storage in autonomous or connected energy systems; or producing very large quantities of hydrogen from dedicated renewables installations.

Two commercial technologies and one emerging technology are considered here: Alkaline, PEM and Solid Oxide respectively, though at least one company has anion-exchange membrane or 'alkaline PEM' technology. As with fuel cells, the different technologies have largely different supply chains, but strengths and weaknesses are largely common and are discussed together. As with some other applications considered earlier, AC-DC conversion (the power supply) is a major cost contributor, and this is expected to become even more prominent at higher future production volumes when stack technology itself becomes cheaper. However, as explained in the critical component selection description, power electronics components are essential for a very wide range of applications beyond electrolysers, and are not examined in detail here.

5.8.2 Supply chain description

Electrolysers – Alkaline

Alkaline electrolysis is a commercially mature technology that has been used for industrial hydrogen production for more than 100 years. The supply chain shares commonalities with the chlor-alkali electrolysis industry, but the alkaline water electrolysis systems typically deployed today are of much smaller scale than chlor-alkali, and so is the overall market. No particular material or component stands out in cost or supply risk. The main cost contributors are the cell components – anode and cathode, as well as the bipolar plates and the membrane or diaphragm, depending on the specific design. Some system integrators use their own proprietary membrane chemistries, while others source from a limited selection of suppliers globally.

Alkaline electrolysis is commercially proven as a base-load hydrogen generator, and suitable system design could make it viable for more variable and intermittent operation profiles.

Europe is one of the leaders in today's global alkaline electrolysis industry with the two major manufacturers, Nel and Hydrogenics, producing in Norway and Belgium respectively, and with other companies such as McPhy gaining momentum. Major players such as ThyssenKrupp have technologies used for chlor-alkali production which could be used for water electrolysis. China, Japan and the US also have production capacity, but are less active in the global market than the European actors. European companies are positioned well to benefit from market growth.

The components for alkaline electrolysers can generally be sourced within Europe. Most of the components used in anode, cathode and bipolar plates are more-or-less standard industrial materials, produced to the specifications of the system integrators. The diaphragm materials are crucial for performance and although standard materials exist, some system integrators use their own proprietary designs.

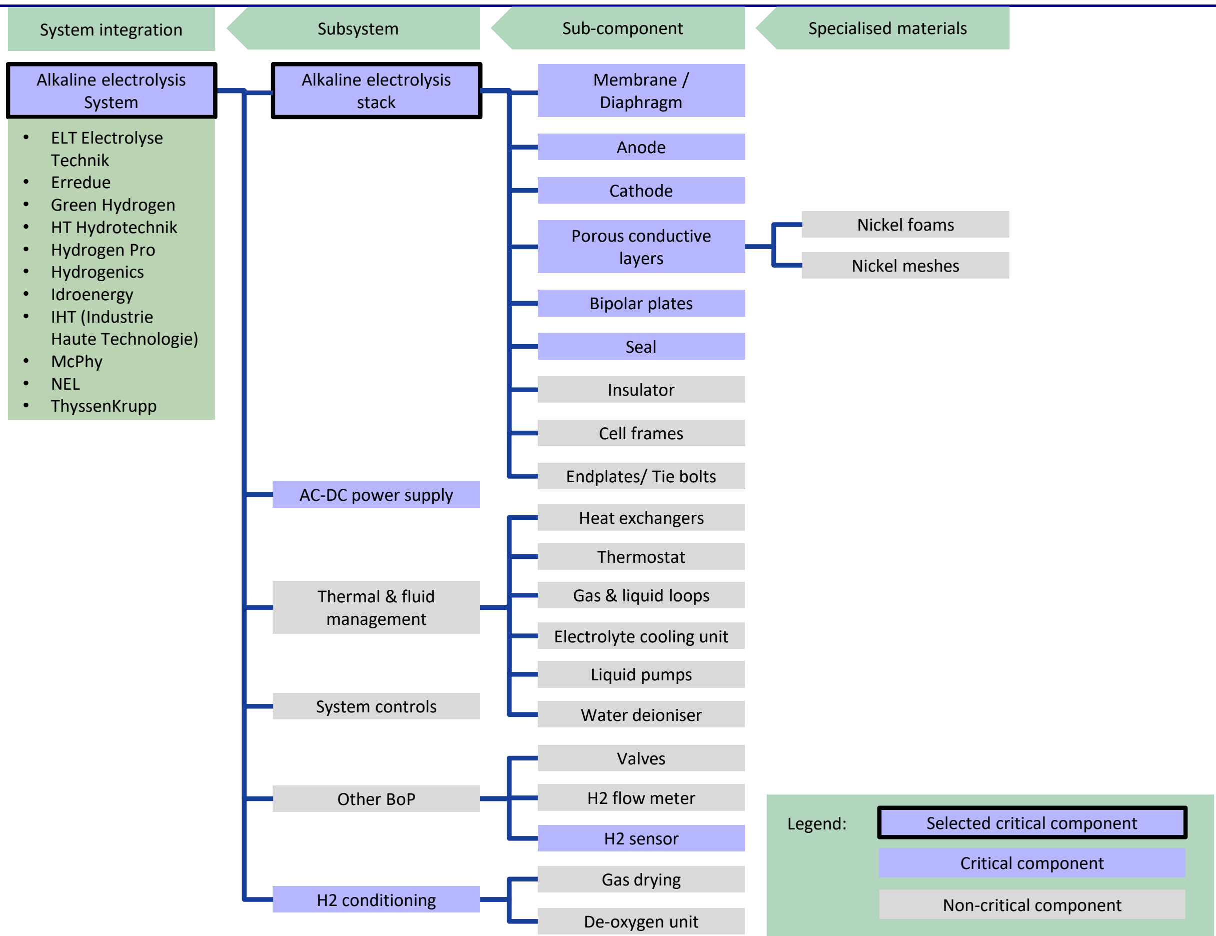


Figure 30: Alkaline electrolyser supply chain structure with European integrators

Electrolysers - PEM

The PEM electrolysis supply chain shares some similarities with its alkaline counterpart as far as system components are concerned, though since there is no liquid electrolyte to be pumped and filtered, the PEM balance of plant is simpler. In stack components, PEM electrolysers resemble PEM fuel cells to some extent, though due to the higher voltages, corrosion-resistant materials such as titanium are used, making many components costly. PEM electrolyser catalyst compositions are different from PEM fuel cells. The main cost contributors to the system are the stack (40%-60%), followed by the power electronics (15%-21%)[142]. Within the stack, the core components that drive the cost are the layers of the MEA. Titanium-based bipolar plates and meshes are typically used[143].

PEM electrolysis is a much younger technology than alkaline, though it has benefitted from PEM FC research and development. Its commercialisation was pioneered in the US, building on developments for the military. Several North American companies have developments or products including Giner, now in partnership with Spanish company H2B2, and Proton OnSite, now owned by Norway's Nel, as well as Hydrogenics in Canada. European developers such as Siemens, Areva, and ITM Power are also commercialising their own PEM electrolysers, most of them in view of expected market growth as part of the energy transition. There is little

[142] Colella et al. 2014 'Techno-economic Analysis of PEM Electrolysis for Hydrogen Production"
https://energy.gov/sites/prod/files/2014/08/f18/fcto_2014_electrolytic_h2_wkshp_colella1.pdf (slide 10)
[143] FCHJU Development of Water Electrolysis in the European Union, 2014 (p.35)

public information on sourcing of components by the system integrators, but many of the supply chain companies currently supplying PEM fuel cell integrators also offer components for PEM electrolysers. This means that Europe is well positioned all along the PEM electrolyser supply chain, however, the electrolyser-specific supply chain is in general less developed compared with PEM fuel cells as there are fewer electrolyser manufacturers.

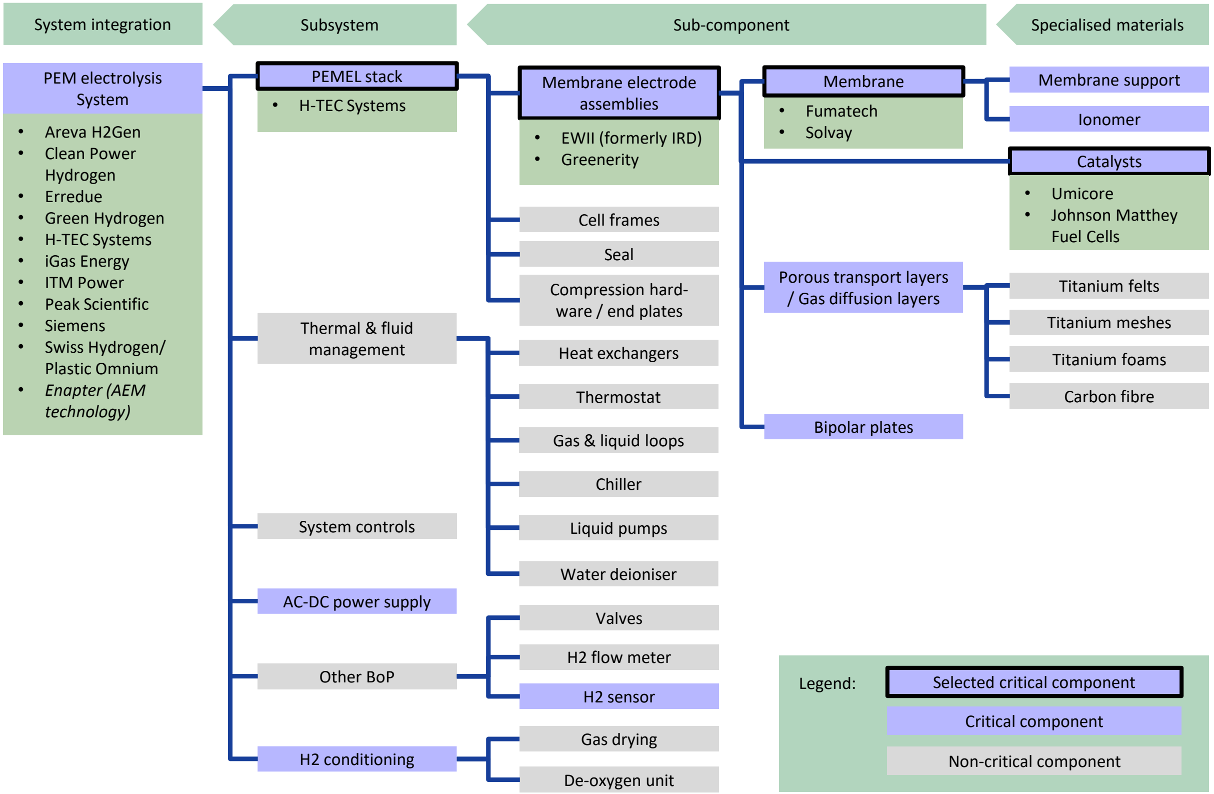


Figure 31: PEM electrolyser supply chain structure with European integrators

Electrolysers - SOEC

The system breakdown and hence the supply chain for solid oxide electrolysers resembles in large parts that of solid oxide fuel cells, plus some hydrogen-conditioning balance of plant as in other electrolyser technologies. They are much earlier in the development cycle, though some developers are also working on reversible solid oxide systems that can operate in fuel cell and electrolyser mode, with German-based Sunfire demonstrating a system in use and French company Sylfen showing an early demonstrator. The components for SOEC at the stack level are largely the same as in SOFC, although less optimisation for electrolyser operation has taken place to date. Although reliable cost analysis is lacking due to the early stage of commercialisation of the technology, indicative results from published analyses suggests that stack cost contributes about 35% to overall system cost[144]. As with SOFC, the repeat cell layers within the stack are most critical and the highest contributors to overall stack cost.

SOEC as a technology is globally at the demonstration stage, and European actors appear to be leading commercialisation. There is some activity in the US, but Europe is ahead with Sunfire, Sylfen, Haldor Topsoe, and SOLIDpower all engaged. Given the early stage of the technology it is not yet clear what role SOEC will

[144] James et al 2016 'Techno-Economic Analysis: Water splitting technologies and metrics ' https://energy.gov/sites/prod/files/2016/05/f31/fcto_awsm_wkshp_5_james.pdf

play in the future mix of electrolysis technologies, though in principle it could help to bring down costs and raise (electrical) efficiencies significantly.

Similar to SOFC, Europe has a breadth of suppliers and developers with excellent knowledge of the technology and the key stack components, though few of the European suppliers have experience with larger volume manufacturing.

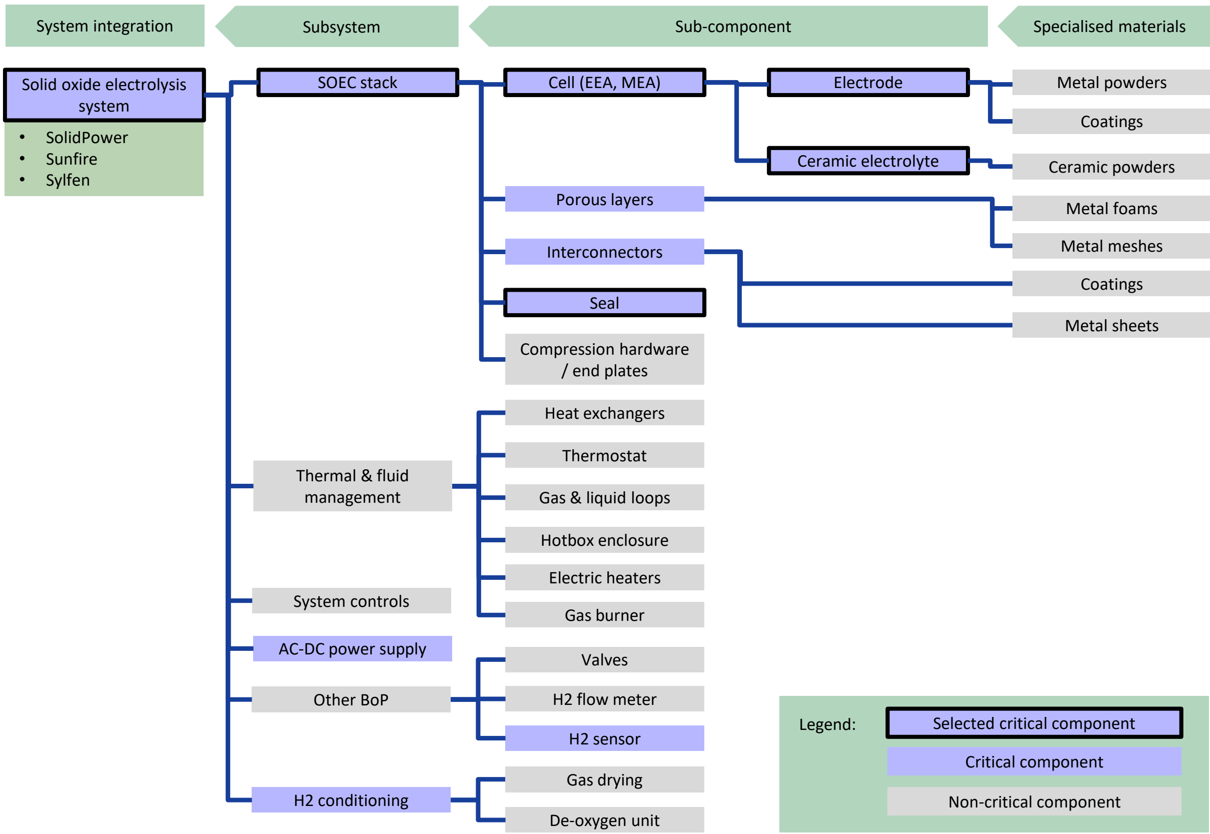


Figure 32: Solid oxide electrolyser supply chain structure with European integrators

As is the case with the industry actors, the KBA sector in Europe is very active in electrolysis and strong in many of the related areas of expertise, across all electrolyser chemistries. Electrochemistry skills are strong in many regions of Europe, as is stack and system expertise. Europe is probably leading globally in terms of solid oxide electrolyser research, and is on a par with other regions in PEM and AEL. Catalysis, fundamental analysis and modelling, cell, stack and system characterisation, and energy system modelling are all represented.

5.8.3 Critical components

The critical components for each FC chemistry associated with this application are included in the tables below. There is more detail on the critical components in Section 7.

Table 66: AEL Electrolyser critical components

Component (AEL)	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Seals	Sub-component	5	
Bipolar plates	Sub-component	5	
Membrane / diaphragm	Sub-component	5	
Porous conductive layer	Sub-component	5	
AEL stack	Sub-system	5	7.3
AEL system	System	5	5.8
Anode	Sub-component	4	
Cathode	Sub-component	4	
Deionisation	Sub-component	4	
Hydrogen sensors	Sub-component	4	
H2 conditioning	Sub-system	4	
AC-DC power supply	Sub-system	4	

Table 67: PEM Electrolyser critical components

Component (PEM)	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Catalyst	Specialised materials	6	7.14
Membrane	Sub-component	6	7.11
Membrane electrode assemblies	Sub-component	6	7.7
PEMEL stack	Sub-system	6	7.3
Ionomer	Specialised materials	5	
Porous transport layer / gas diffusion layer	Sub-component	5	
Bipolar plates	Sub-component	5	
PEMEL system	System	5	5.8
Membrane support	Specialised materials	4	
H2 sensor	Sub-component	4	
H2 conditioning	Sub-system	4	
AC-DC power supply	Sub-system	4	

Table 68: Solid Oxide Electrolyser critical components

Component (SOEL)	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Cell (EEA, MEA)	Sub-component	6	7.8
Ceramic electrolytes	Sub-component	6	7.8
Electrodes	Sub-component	6	7.8
Seals	Sub-component	6	7.13
SOEL stack	Sub-system	6	7.3
Interconnectors	Sub-component	5	
Porous metal layers	Sub-component	5	
SOEL system	System	5	5.8
H2 Sensor	Sub-component	4	
H2 Conditioning	Sub-system	4	
AC-DC power supply	Sub-system	4	

5.8.4 System-level SWOT/gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 69 below shows the results of the SWOT analysis for electrolysers as a whole carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of electrolysers*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 69: SWOT for European electrolysers supply chain

STRENGTHS	WEAKNESSES
• Mature technology • Early history in Europe with electrolyser deployment in, e.g. fertiliser manufacture • Several strong electrolyser manufacturers, across different countries, with own stack technology - roughly half of electrolyser manufacturers are in Europe, including most of the larger ones • Expertise in PEM, Alkaline and SOEC, including in materials and components • Good links with HRS integrators, or internal capabilities to do this integration • Generally strong local sourcing, including most components • Very strong research base in electrolyser technology and science • Good reliability achieved with alkaline and PEM electrolysers	• Small and fragmented industry • Little supply chain optimisation • Potential lack of economic competitiveness compared to other means of hydrogen production, e.g. SMR • The range of technologies being developed leads to some duplication of effort and fragmentation of approach, given the currently small market with companies still building profitability • Market is dependent on policy for electricity, and renewables in particular

OPPORTUNITIES	THREATS
• Power-to-X gaining traction as means to integrate and balance renewables as well as decarbonise heat and produce fuels • Latest Renewable Energy Directive is likely to support a wide range of renewable hydrogen-based fuels • Remote hydrogen production in conjunction with renewables could offer local benefits • Solid oxide electrolysers offer promise for operating cost reduction • 'Green' chemicals and refining may offer a new market opportunity • Supply chain crossover with FC could help lower costs	• Dominance of non-European competitors such as Hydrogenics • Renewable or otherwise 'clean' hydrogen may not get the support needed to make it competitive • Industrialisation may take place outside the EU or not bring costs down as far as anticipated • Low carbon, non-renewable hydrogen such as SMR+CCS may emerge and be lower cost

Technology gaps in electrolysers mostly relate to manufacturing scale-up and supply chain optimisation; no breakthroughs are required for performance. Support mechanisms are evolving and some gaps in recognition of 'green' hydrogen exist. Large-scale manufacturing capacity is not yet built for most producers. Electricity market structures and tariffs often add significant cost which reduces the competitiveness of the hydrogen produced; this may represent a regulatory gap.

5.9 Hydrogen storage

5.9.1 Application introduction

Hydrogen storage comprises a very wide range of technologies with dramatically different supply chains and scales, as well as levels of commercial readiness. These include compressed and liquid storage, plus solid state materials (e.g. metal hydrides), liquid organic carriers and cryo-compressed. Some of these technologies also have different maturity at different scales. The different chains are not broken down here, except for compressed hydrogen tanks, which are a dominant application in transport and are still maturing. On-board liquid storage for transport is rarely considered today, though if heavy-duty transport applications emerge strongly this may change. Large-scale liquid storage for industrial uses is a mature and established market.

5.9.2 Supply chain description

The supply chain diagram for compressed tanks is shown below. Balance of plant (including in-tank pressure regulators, where used) and the composite materials are the major cost contributors[145].

Europe has strong skillsets in a wide range of storage technologies at many scales, including world-leading science in novel storage technologies. For the different technologies mentioned above, Europe is generally well-positioned, with suppliers or developers in all areas. Although compressed storage appears to have many players, not all produce tanks in Europe, and this remains a weakness in the supply chain. Hydrogen compressed tank supply has some strong Asian and N American actors, with specialist materials, notably high-grade carbon fibre, coming more from Asia. Valves and regulators are an important area for cost

[145] https://www.hydrogen.energy.gov/pdfs/review13/st100_james_2013_o.pdf

reduction and good opportunities exist for export, though there are few suppliers generally and both the regional and the global supply chain need strengthening.

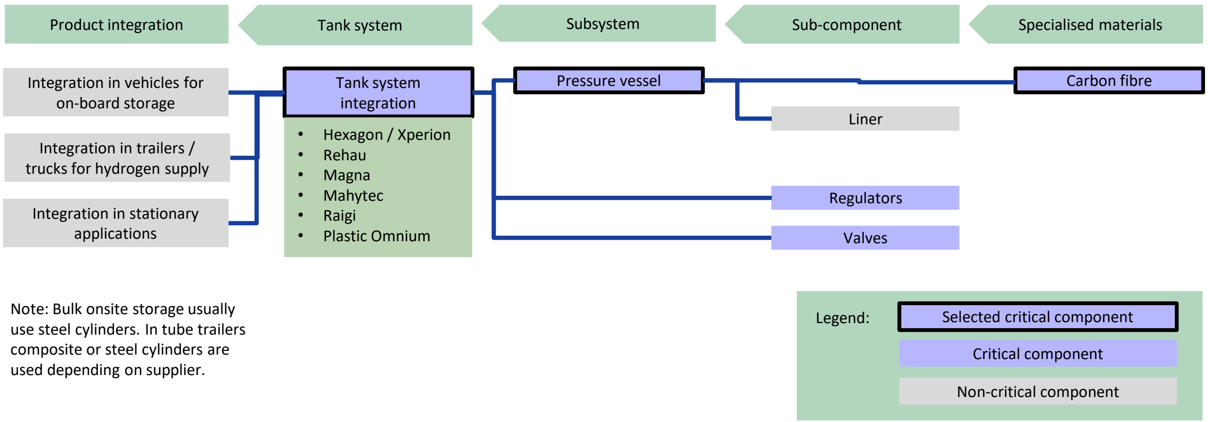


Figure 33: Hydrogen storage supply chain structure with European integrators

While Europe has a very deep and broad set of capabilities in hydrogen storage generally, it is spread across a great many areas, including solid state systems. Nevertheless, aspects directly relevant to the high pressure storage considered here include composite materials, carbon structures, tank performance design and modelling, and risk and safety analysis. Overall, European KBAs rank well against their counterparts in Asia and North America, and may even have a slight advantage over the latter, as slightly more activity seems to be underway in Europe.

5.9.3 Critical components

The critical components for each FC chemistry associated with this application are included in the tables below. There is more detail on the critical components in Section 7.

Table 70: Hydrogen storage critical components

Item	Supply Chain Sector	Assessment score (out of 6)	Subsection (if selected)
Carbon fibre	Specialised materials	5	7.15
Regulators	Sub-component	4	
Valve	Sub-component	4	
Pressure vessel	Sub-system	4	7.4
Tank system integration	System	2	5.9

5.9.4 System-level SWOT/gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 71 below shows the results of the SWOT analysis for hydrogen storage as a whole carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of hydrogen storage*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 71: SWOT of European hydrogen storage supply chain

STRENGTHS	WEAKNESSES
• Good EU capabilities in compressed and liquid storage tank manufacture, some hydrides and other carriers • Wide ecosystem around producers, including safety and standards • Capabilities to develop tanks, and several major new entrants including automotive Tier 1 suppliers • Strong science base in solid-state and other novel mechanisms	• Some primary materials come from elsewhere, e.g. C fibre from Asia • European capabilities are not fully translated into local production • Current market is small, costs are high, tanks are not yet optimised • Current tanks are very similar between suppliers - a cheaper, lighter or otherwise better-performing tank developed elsewhere could change markets rapidly • Standards err on the side of caution, driving costs up • Few suppliers exist for some components, which results in high costs and high supply risks
OPPORTUNITIES	**THREATS**
• Interest is very strong, and increasingly includes buses and HGVs which require lots of H_2 • Storage and distribution of hydrogen remains a major challenge, so a cheaper, lighter or otherwise better-performing solution would penetrate rapidly and capture market share • Tank technology has essentially changed little for years, so could be improved	• Any major accident during market development could set back the entire sector • Technologies such as on-demand hydrogen production might be developed to a competitive level • C fibre demand is dominated by aerospace and limited supply means not enough may be available for pressure vessels • Development of large transport markets outside the EU might divert tank supply to those

The main gaps in hydrogen storage are related to the availability and cost of tanks and some other components. Carbon fibre availability is a bottleneck and European-based supply could alleviate some concerns about supply risk. Europe's relatively limited industrial supply base is being augmented by new entrants, but these are primarily looking at tank manufacture and supply, and less at materials. Manufacturing scale is also lacking, though it would be comparatively straightforward to increase existing capacity given investment. Low-cost reliable components such as regulators would also help advance the industry and support Europe's competitive position.

5.10 Fuel processors / reformers

5.10.1 Application introduction

Conversion of hydrogen-rich resources into high hydrogen-content gas streams is required for many applications to function and for the effective use of existing resources. For this study, natural gas (methane) is the most relevant hydrogen resource and so the main focus of the analysis below is on methane reforming. However, many component types are common or similar, and so much of the supply chain is closely linked for fuel processors that use other inputs, such as liquid fuels.

Large-scale steam reformers (100 kW and over) are standard industrial equipment and Europe competes on a level footing globally, with supply chain strengths from catalysts (e.g. BASF, Johnson Matthey) through components to design and build of reactors (e.g. Linde, Jacobs). Smaller-scale systems have been developed over the past few decades primarily for FCH applications, and Japan leads globally in very small scale methane reformers, through Tokyo Gas and Osaka Gas. Despite the production of hundreds of thousands of units, however, costs remain higher than is required for full competitiveness at very small scales. WS Reformer and some other European specialists also have strong offerings. HyGear in the Netherlands makes somewhat larger reformers and many of the fuel cell CHP companies buy or assemble reformers to integrate into their products.

In the past, the barriers to entry in this sector were high due to the requirement for specialised reformer and catalyst design knowledge, as each reformer was to a large extent unique. However, as reformers become simplified and commoditised, opportunities for companies to enter the reformer manufacturing business are expected to proliferate. It may be that any manufacturing company could make the reformers.

In some instances, e.g. with SOFC and MCFCs, the functionality of the reformer is blended with that of the fuel cell, through a mix of fuel processing in the reformer vessel and inside the fuel cell itself. These systems also need further cost reduction however, through a combination of performance improvement (e.g. size reduction), system simplification, and mass production. Final gas cleanup is typically the most difficult aspect of reforming, i.e. removing CO before use in a PEM or sulphur for all FC applications.

5.10.2 Supply chain description

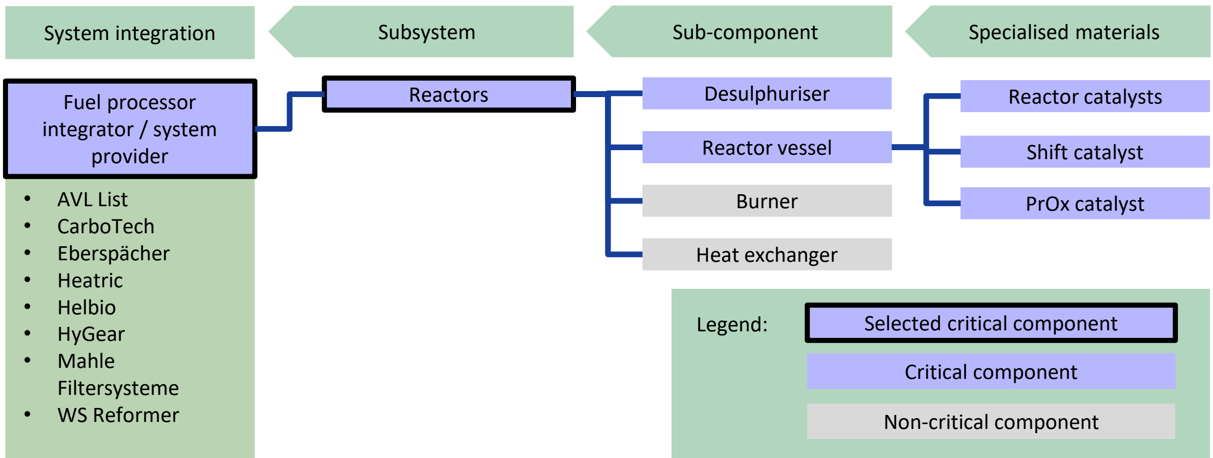


Figure 34: Fuel processor supply chain structure with European integrators

Europe has strengths in reformer catalysis, system design and modelling and in reformer systems in general, though historically much of that strength has been applied at large scale. However, smaller-scale fuel processing using different fuels (including very small fuel processors such as microchannel reactors), and the links between fuel processing and any stationary fuel cell applications mean that strong KBAs are present in many of the different aspects. European KBAs are on a similar level of capability to those in both North America and Asia.

5.10.3 Critical components

Fuel processor technologies in general are mature and well understood at large scale, and at small scale in some cases, e.g. within Ene-farm in Japan. However, integration of units smaller than the main industrial scales requires highly specialised know-how, as does reactor design and manufacture, in order to approach cost and performance targets.

Table 72: Fuel processor critical components

Component	Supply chain sector	Assessment score (out of 6)	Subsection (if selected)
Reactors	Sub-system	6	7.6
Fuel processor integration /system provider	Integration	6	5.10
PrOx catalyst	Specialised materials	5	
Reactor catalyst	Specialised materials	4	
Shift catalyst	Specialised materials	4	
Desulphuriser	Sub-component	4	
Reactor vessel	Sub-component	4	

5.10.4 System-level SWOT/gap analysis

SWOT analysis of the European supply chain and key components and discussion of gaps

Table 69 below shows the results of the SWOT analysis for fuel processors as a whole carried out using the approach explained in Section 5.1.1. In the SWOT, strengths, weaknesses, opportunities or threats *related to the European supply chain* are shown in **black text**, whilst strengths, weaknesses, opportunities or threats *related to the conditions for deployment of fuel processors*, but which directly affect the EU supply chain, are shown in **blue text**.

Table 73: SWOT of European fuel processor supply chain

STRENGTHS	WEAKNESSES
• Good EU capabilities in reformer design and build, particularly at large scale • Wide ecosystem around producers, including specialised components, and safety and standards • Capabilities to develop technologies at other scales • Strong science base in catalysis, modelling, heat transfer etc	• Several specialist companies ceased activity during periods of limited FCH support • Production scale is currently limited • Current market is small, costs are high, processors are not yet optimised • Much of the policy focus is on green hydrogen, so less work on reforming • Few suppliers exist for some components, which results in high costs and high supply risks

OPPORTUNITIES	THREATS
• Increased interest in hydrogen for heat means that bio- or even fossil gases are of interest for hydrogen • Storage and distribution of hydrogen remains a major challenge, so on-site production remains an interesting option • Outside of Japan, no dominant suppliers exist, so markets can be developed • One or more strong European producers with the right product could find large global markets accessible	• Japanese manufacturers could more aggressively target Europe or other markets • Pure hydrogen from renewables, including cost-effective electrolysis provision, could reduce interest and the available market

Much of the supply chain for fuel processors relies on know-how and expertise around reactor vessel design, catalysis, thermal and fluid management. Europe is well-placed in all of these areas, and has some organisations with deep skills specifically in fuel processing for fuel cells. Gaps are primarily in the mass-production of units, and the cost reduction linked to that. This can be ameliorated to some extent through increased demand and hence increased production capacity.

5.11 LOHC and ammonia

5.11.1 Application introduction and supply chain overview

As interest in large-scale renewable or low-carbon hydrogen grows, methods of storing and transporting it, particularly for long distances, become more important. Liquid organic hydrogen carriers (LOHC) and ammonia are increasingly considered, though very few LOHCs are under serious development. Nevertheless, they could form an important part of the future value chain. Europe has conventional industrial strengths in ammonia technologies, plus some smaller-scale developers, and one or two organisations developing LOHC. LOHC and ammonia are in the early stages of development as hydrogen carrier technologies. The supply chains are relatively straightforward, and currently somewhat ad-hoc, driven by the product integrator. The description here is therefore intended as an overview only; the analysis is not carried forward unlike other technologies.

In addition to the industrial actors, which include Areva and Hydrogenious, a few KBAs are active in the area. Japanese company Chiyoda has been working on LOHC for many years and has the largest demonstration plant, but few other activities are happening globally. In a currently very limited application space, Europe is well placed in terms of both industrial actors and KBAs, including those on reaction chemistry and catalysis.

5.11.2 Critical components

Both the LOHC and ammonia supply chains are comparatively straightforward and well understood. The LOHC chain is evolving but the main proponents of the technology are focused on the use of conventional catalysts, chemicals and (de-)hydrogenation equipment as far as possible and so no critical components have been identified.

6 Mapping of European FCH supply chains by technology

6.1 Introduction

While Section 5 describes the supply chain by **application**, in this section it is discussed by **technology**, to allow common components and their supply characteristics to be examined. Where the earlier discussion had something of a focus on systems and integrators, the findings in this section are focused at the component and materials level, laying out the critical components in the technology's supply chain and the actors associated with them. A more detailed description and analysis of the critical components is then given in Section 7. It is important to reiterate that only the **selected** critical components are assessed in more depth, as a representation of the important issues and opportunities facing the industry. As explained earlier, this selection is based on criteria that include socio-economic impact, and does not imply that other components are not critical to the technical or commercial feasibility of a system.

The fuel cell and electrolyser technologies consist primarily of a stack and supporting subsystems. There is a particularly large overlap between some of the subsystems across the technologies; discussed below. Two specific subsystems, fuel processors and hydrogen storage, are discussed in more detail in dedicated sections, 6.9 and 6.13.

Power electronics and system controls are very similar across the different fuel cell technologies. While they will vary by application and scale of the system, the chemistry is not the determining factor. Other balance of plant (BoP) components can vary widely with the chemistry of the fuel cell. Selection and sizing of components like filters and valves will depend on the operational characteristics of the technology, and operating temperature will have a considerable impact. Thermal management differs between high temperature technologies, such as SOFC, and low temperature technologies, such as PEMFC and DMFC.

6.2 PEMFC

Polymer Electrolyte Membrane (PEM) fuel cells are built up from a polymer membrane, with supporting layers, catalyst, fluid management structures etc. PEM is the dominant technology used in transport and it is also commonly used in stationary applications. The relatively low operating temperature (usually below 100°C) allows rapid start-up, while its high power density and specific power makes it good for transport and portable needs. The durability of PEM to voltage and temperature cycling relative to other chemistries is a further benefit.

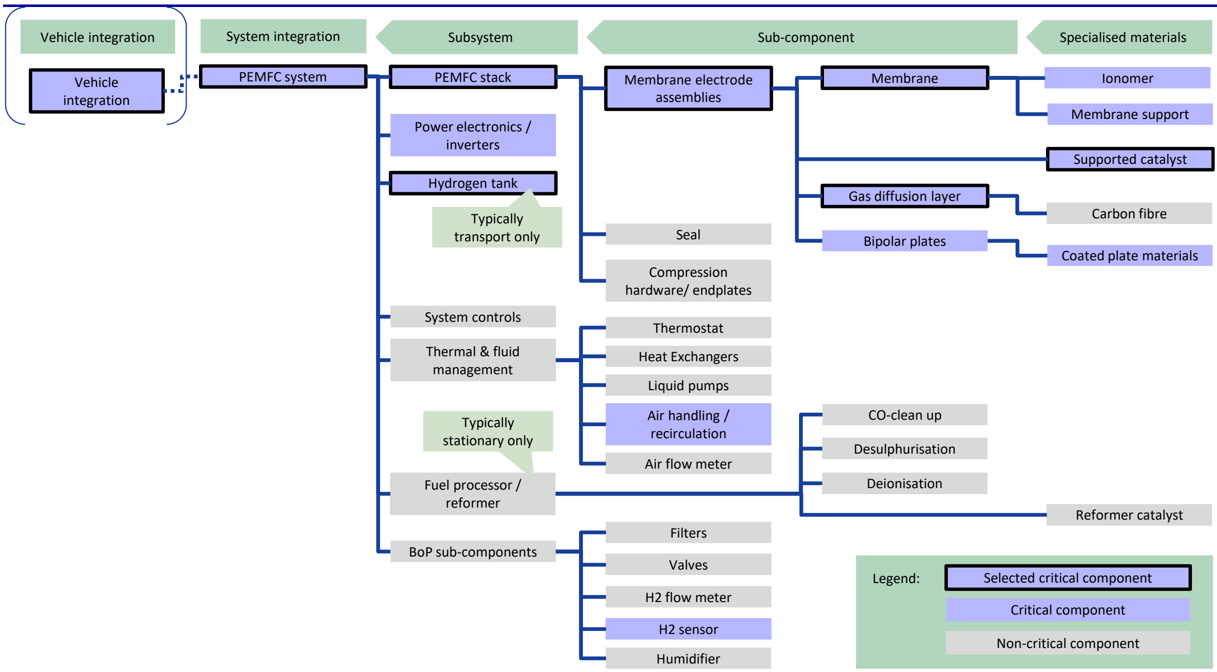


Figure 35: Generic PEMFC supply chain structure

Figure 35 shows a generalised supply chain for PEM in both transport and stationary applications. As before, the components that scored 4 or above in the ranking are deemed 'critical', while only a subset of those are selected for further investigation.

For classification in the database, stationary applications 'end' at the system integration stage and do not have the additional integration step that happens when a system is integrated into a vehicle in transport applications. Conversely, the transport applications generally use pure hydrogen as fuel, and thus do not require the fuel processor that is common in many stationary applications, for converting natural gas or other fuels into a hydrogen-rich stream. However, transport requires a hydrogen storage tank, rarely needed in stationary cases. The only other major supply-chain difference between transport and stationary PEM applications is the material for the bipolar plates: carbon/graphite is typically used in stationary and metal more often in transport. 'Coated plate materials' hence do not figure in the supply chain map for stationary applications.

The EU has multiple players at each stage of the PEM supply chain, and some, for example in bipolar plates, catalyst, and GDLs are world-leading. In MEAs they rank on a par with other regions of the world, but lag slightly in industrial membrane capability, mainly behind the USA. China is also increasing its capabilities in this area.

Europe is generally well-represented in the component supply chain for fuel cells and hydrogen technologies for transport (Figure 36), with companies nominally capable of supplying high quality components competitively with overseas peers in almost all areas. However, some of the more specialised companies are small and not always financially stable, and so may require further support to become competitive. While in principle the components for many applications only vary slightly and might be developed by the same suppliers, in practice, the industry relationships, quality and cost expectations, and many other factors mean that specialisation is likely. This specialisation will almost certainly occur downstream of the MEA, and possibly earlier, for stationary and transport uses and perhaps even between applications, though this will change as the sectors mature.

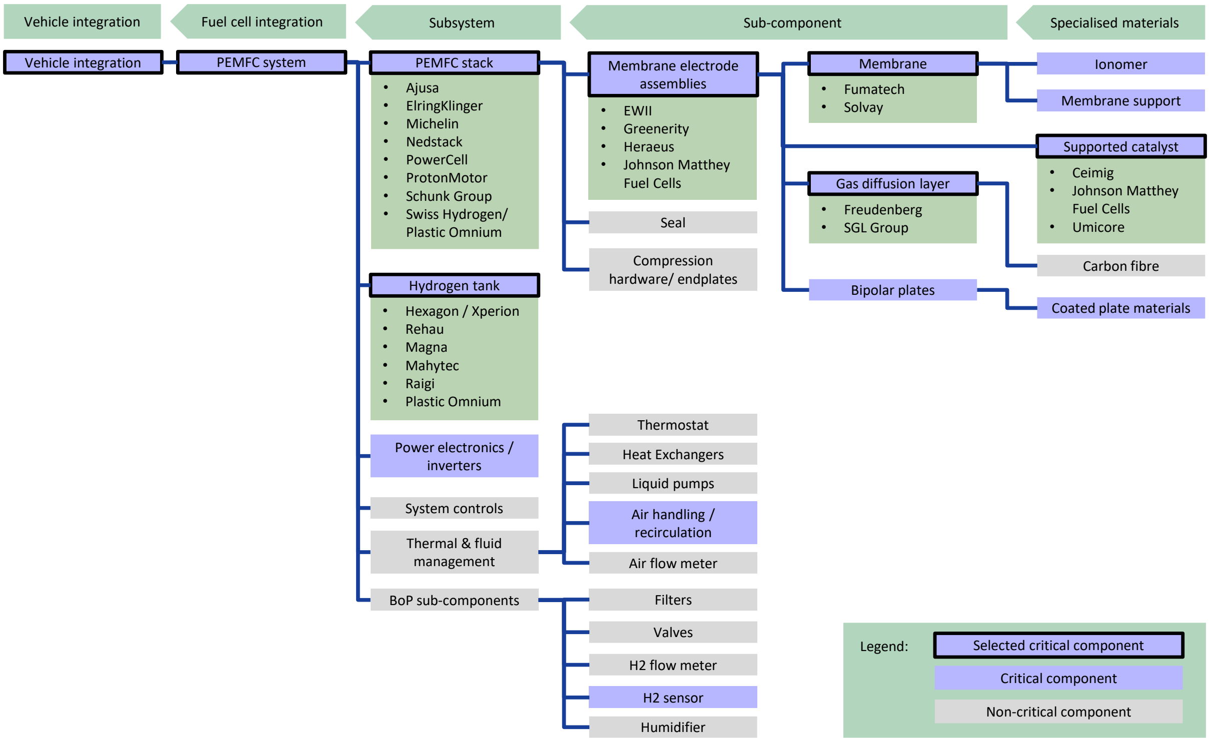


Figure 36: PEM Transport supply chain structure with European actors in selected critical components

Stationary PEM systems, materials and stack components are very similar to those in transport applications. Note that some of the listed stack suppliers listed in Figure 37 focus on certain applications (e.g. back-up power systems) but not on others. Some dimensions and exact compositions may vary, such as changes in catalyst composition to accommodate higher levels of fuel impurities, or thicker membranes for longer lifetimes. Some elements can be made of different materials, such as graphite instead of steel for bipolar plates – the latter typically have a shorter lifetime and may not be used for CHP applications, for example. However, transport has relatively low utilisation rates compared to stationary applications and therefore cheaper metallic bipolar plates are used. Metallic plates also have a higher current density, which is important in transport because of space requirements and the need for high power densities. Systems integration is considerably more varied, as it may include fuel processing and heat exchanger requirements. The single biggest cost contributor is the stack[146], dominated by the repeated layers in each cell. The fuel processor is also high cost.

[146] FCHJU – "Advancing Europe's energy systems: Stationary fuel cells in distributed generation" 2015 http://www.fch.europa.eu/sites/default/files/FCHJU_FuelCellDistributedGenerationCommercialization_0.pdf

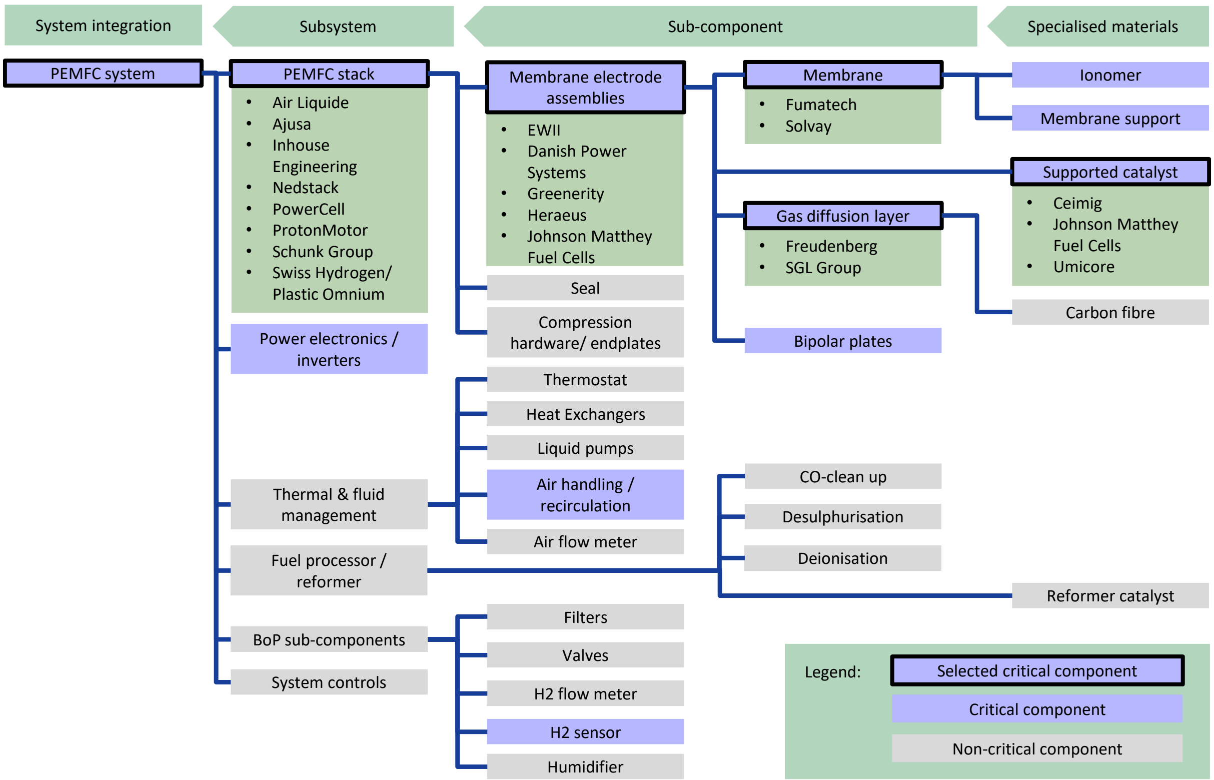


Figure 37: PEM Stationary supply chain structure with European actors in selected critical components

The majority of component level companies only produce one component in the supply chain and there is little vertical integration within PEM supply chains, apart from membrane electrode assemblies which may be manufactured by those who produce the membrane or catalyst materials.

The large range of applications and growing global market for PEMFC has resulted in an international supply chain, with many European companies procuring from and supplying to actors inside and outside of the EU. Exclusive arrangements are rare or non-existent, as this would increase risk, though in practice often only one company will supply the exact component required. Much of the supply chain is immature, and sparsely populated with credible players globally.

The core unit of a PEMFC is the cell inclusive of the MEA, bipolar plates, and seals. While there are technical challenges for bipolar plate and seal manufacture, there are many potential capable actors if the market matures. The MEA and its sub-components, however, were selected because they represent a large fraction of the system cost and require unique technical and manufacturing capabilities. To understand differences across multiple applications, the stack and the application integrator were selected for further examination.

6.3 DMFC

Whilst most other FCs are fuelled by hydrogen, DMFCs run on methanol, input straight into the anode. As with PEMFCs, DMFCs use a polymer membrane as an electrolyte. The storage and transport of methanol is simpler than dealing with compressed hydrogen. DMFCs are often used for portable applications with low-power requirements, such as portable power packs, and operate between 60°C and 130°C.

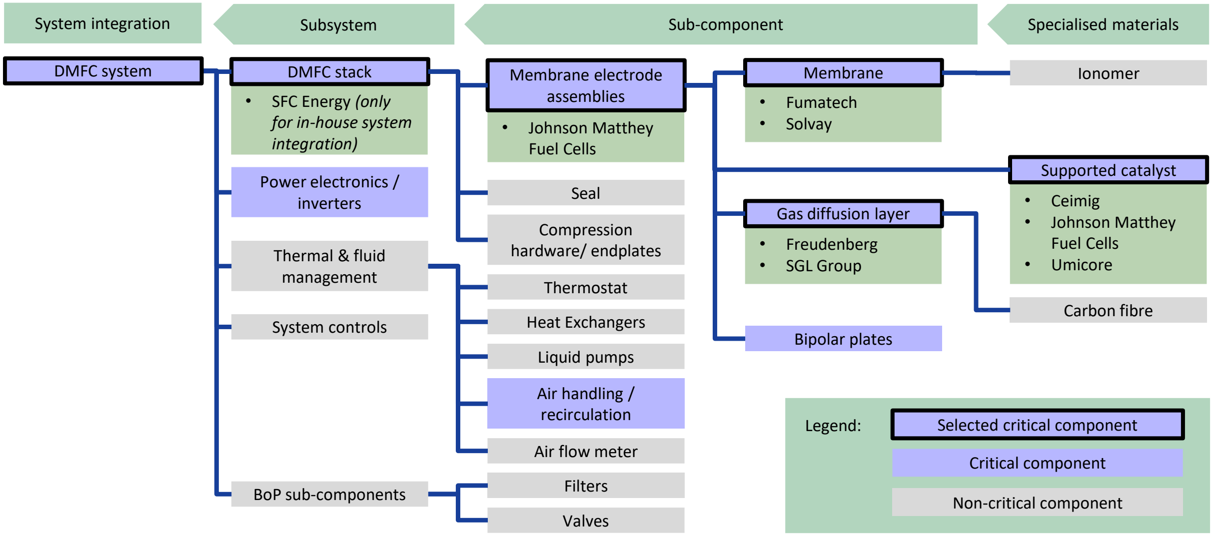


Figure 38: DMFC supply chain structure with European actors in selected critical components

The membrane electrode assembly in DMFC is often produced by the system integrators. The stack also often belongs to the system integrator and there is quite a high amount of vertical integration in DMFC supply chain up to the sub-component level.

The components and materials associated with the membrane electrode assemblies are often similar to those used in PEMFC, as the polymer electrolyte is the same but with a different catalyst (platinum-ruthenium) on the anode to allow for the use of methanol as the fuel. Therefore, the actors for many parts of the membrane electrode assemblies are similar to those for PEMFC. The use of this catalyst means that a fuel processor or reforming stage is not needed.

The familiar names of Umicore and JM are strong European actors for catalysts, producing for the European domestic market and also exporting their products outside of Europe. Although the market is small for DMFC applications, these companies produce the required catalyst. The similarities with the PEMFC technology results in the same players producing membranes. Solvay and Fumatech are the largest European actors in this component, but the market dominant player is based in the US. Similar to gas diffusion layers in PEMFC, Europe has a strong position in this component.

DMFC use composite bi-polar plates, which have increased costs when compared to metallic plates used in transport PEM applications.

European KBAs are strong in catalysis and electrocatalysis in a wide range of areas, including those relevant to DMFC, and in materials, systems and control.

The rationale for selecting DMFC critical components is similar to PEMFC. While there are technical challenges for bipolar plate and seal manufacture, there are many potential capable actors if the market matures. The MEA and its sub-components were selected because they represent a large fraction of the system cost and require unique technical and manufacturing capabilities. The stack and the application integrator were also selected for further examination to understand their role in the supply chain.

6.4 SOFC

Solid oxide fuel cells use a non-porous ceramic as their electrolyte and operate at temperatures as high as 1000°C. This ensures the ionic and electrical conductivity of its parts, and removes the need for a noble metal catalyst. However, this high temperature limits the choice of suitable materials for use in SOFCs. As it is a solid-state system it is simpler than PAFC and MCFC which require 3 phases, compared to the SOFC's 2. This provides the advantage of reduced corrosion and eliminates the need for electrolyte management[147].

SOFC technology requires less fuel processing before the fuel can be used in the cell as SOFC can operate with higher levels of CO. Therefore, only desulphurisation needs to occur, which changes the sub-system name to 'Pre-reformer' for SOFC.

This chemistry only has stationary applications and ranges from small micro CHP units to large-scale primary power and CHP. The high operating temperature of these cells makes CHP an attractive option.

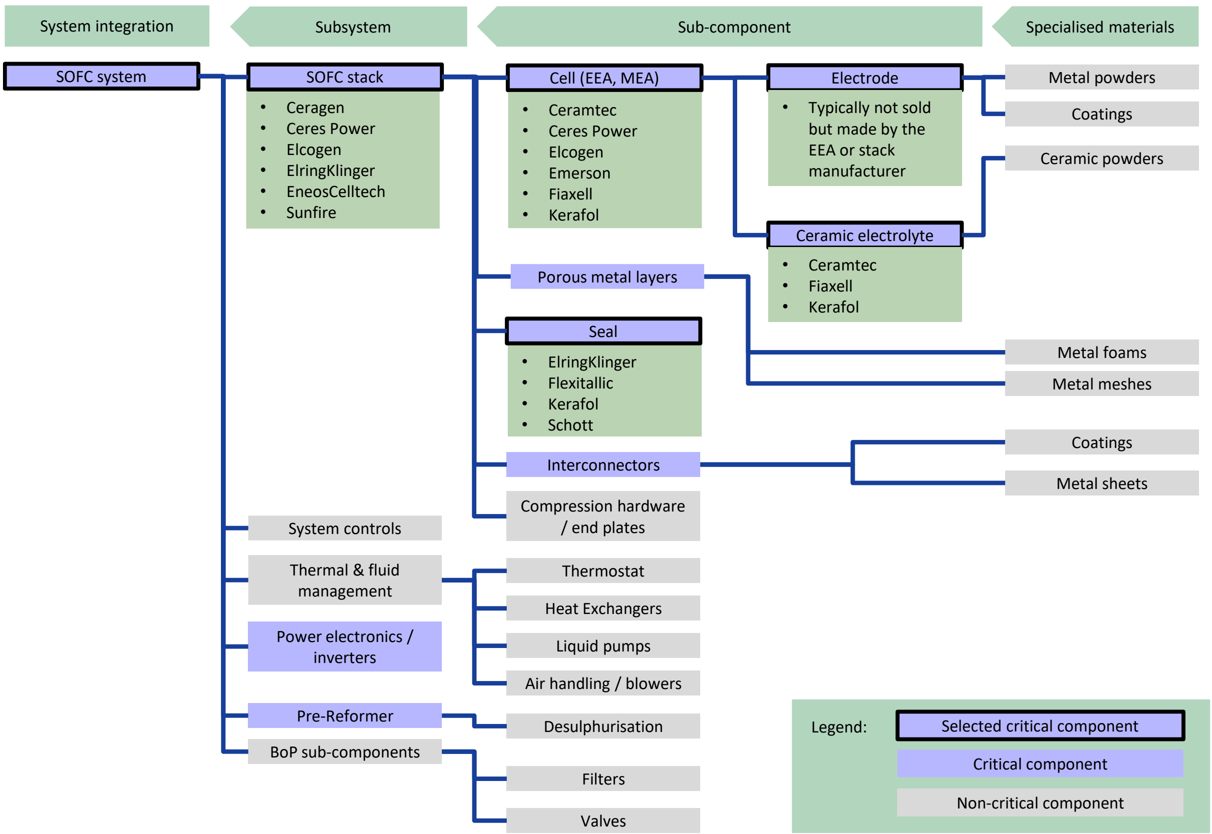


Figure 39: SOFC supply chain structure with European actors in selected critical components

Unlike other FC technologies, there is very little commonality in the supply chains of SOFC system integrators. This is even true for SOFC actors with the same end-use applications and is caused by the variety of SOFC system structures and materials. Figure 39 shows a basic structure of a generalised SOFC supply chain. As designs are heterogeneous, few integrators have more than one stack technology, as it becomes hard to manage all the separate components required for each type. Many parallel supply chains tend to exist without major interaction. This results in a large amount of vertical integration in these supply chains, or at least close relationships with suppliers, making the supply chains very narrow, and in some cases fragile.

Europe has a strong range of actors within these SOFC supply chains, especially within the critical components (highlighted in Figure 39). Some companies are actors within only one component. Meanwhile, some actors, like Kerafol, work across multiple critical components. Several European companies also supply components to overseas companies, including in Asia, and could supply stacks or subsystems in the future.

[147] L. Blomen & M. Mugerwa (1993) 'Fuel Cell Systems' ISBN 0306441586

As mentioned, the higher operating temperature of SOFCs, coupled with the cell chemistry, removes the need for a precious metal catalyst due to the higher kinetics of the fuel. Therefore the strength in European precious metal catalyst companies is less relevant to this technology. However, the use of metal and ceramic powders and procurement of materials is still important to SOFC supply chain. As SOFC technologies vary, companies producing powders often have to have the capability to meet many different requirements.

The core unit of an SOFC inclusive of the electrodes, electrolyte and seals were selected as critical components as this represents significant intellectual property both in the composition and manufacture. Ceramic materials are believed to be a commodity, thus they were not included in the analysis. Similar to other chemistries, the stack and the application integrator were selected for further examination to understand differences across multiple sectors.

A wide range of KBAs is active, with skills covering all of the value chain, from fundamental analysis of atomic interactions within ceramic structures to system design and post-use degradation analysis. Some of these KBAs are globally recognised as leaders.

6.5 AFC

Alkaline fuel cells use a potassium hydroxide solution as the electrolyte, permitting the use of several non-precious metals as catalysts. Nickel is an important material because of its resilience to the alkaline content of the cell. AFCs typically operate between 60°C and 80°C, and usually at atmospheric pressure. This chemistry is currently only being used in stationary applications, in particular back-up power and large-scale primary power.

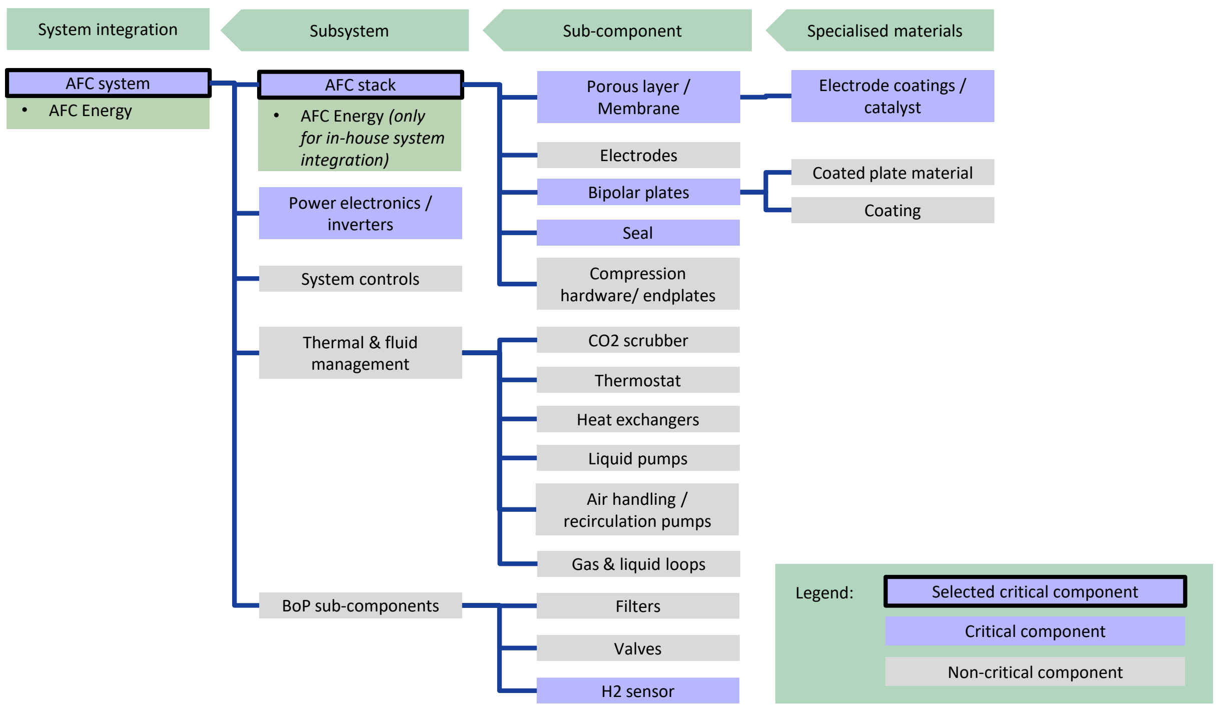


Figure 40: AFC supply chain structure with European actors in selected critical components

AFC systems are actively developed in Europe, targeted at large-scale deployment, but only by AFC Energy. Smaller systems are being sold in small numbers by Israel's GenCell. AFC technology is in a demonstration or early commercial stage and this is reflected in the supply chain, as it is still maturing with many suppliers working on an *ad-hoc* basis. Little work is going on outside of Europe and both AFC Energy and GenCell take advantage of the European market. This positions Europe well in the development of this technology.

Similarly to PAFC, integrators often use their own cells, showing a degree of vertical integration in the supply chain, at least to the sub-component level. The integrators currently also produce the components, such as the electrodes, procuring the catalytic materials in powdered form. Bipolar plates, however, are usually purchased from manufacturers. Some designs may use a membrane to improve the equilibrium of the reaction and to even out concentration gradients in the electrolyte. These membranes are similar to those used in the chloro-alkali industry and are usually sourced from there, unless a more specialised membrane is required[148].

Selected critical components were restricted to the AFC stack and system due in part to the tendency towards vertical integration of AFC manufacturers. This tendency towards vertical integration and the limited number of actors involved leads to a lack of depth or breadth in the supply chain.

Because of the very limited industrial activity, little work is being undertaken at KBAs, though many have relevant skills that could be applied.

6.6 PAFC

Phosphoric acid fuel cells utilise phosphoric acid suspended in a silicon carbide matrix as an electrolyte and porous carbon electrodes, containing a platinum catalyst. PAFCs are one of the most mature FC technologies, having been developed in the 1960s. PAFCs when used for cogeneration are more than 85% efficient, although this is around 40% when used for electricity generation alone. PAFC operating temperatures are approximately 200°C[149]. Due to their lower power densities, with respect to other fuel cell chemistries, PAFCs are relatively heavy and large, and thus have historically been used for stationary applications.

[148] E4tech internal – interviews with expert
[149] L. Blomen & M. Mugerwa (1993) 'Fuel Cell Systems' ISBN 0306441586

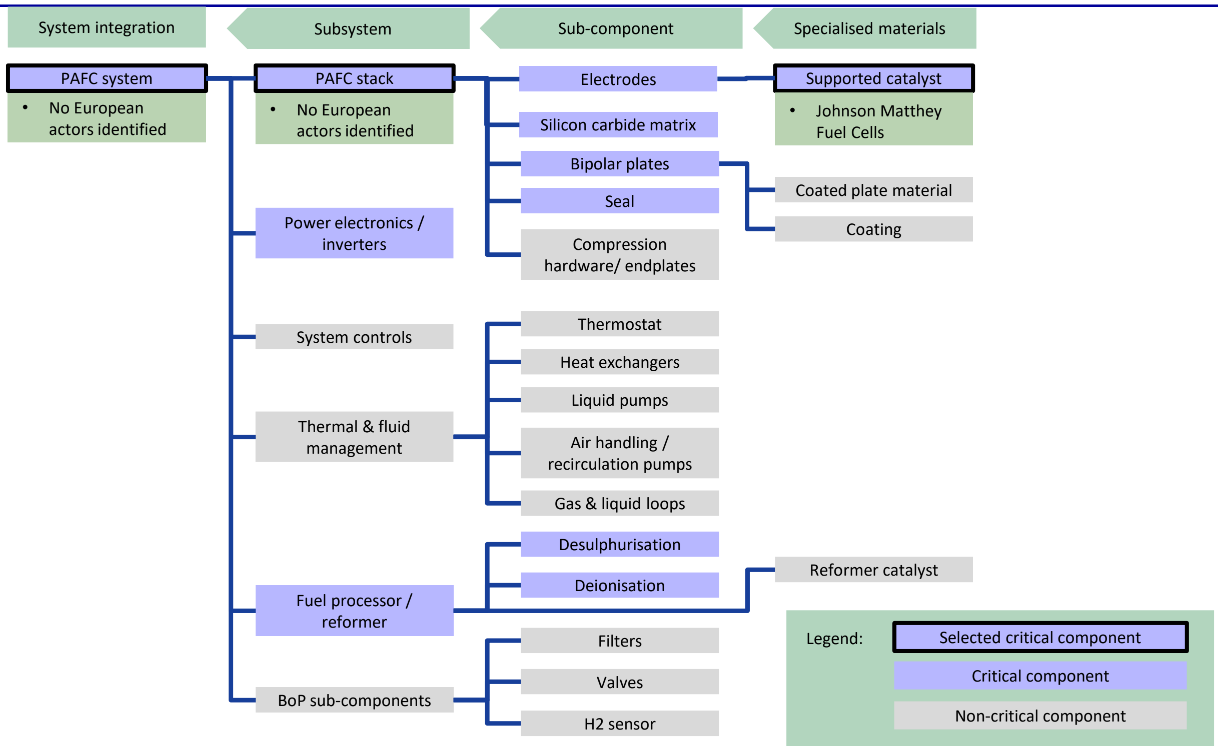


Figure 41: PAFC supply chain structure with European actors in selected critical components

For PAFC, there is European activity in the specialised materials sector of the supply chain, producing specialist platinum catalysts. This is dominated by Johnson Matthey (JM), one of the leading companies in the manufacture of catalysts globally, in many fuel cell chemistries. System integrators commonly use their own stack technology and may procure materials and components for these through specialised actors. The silicon carbide matrix within the cell is unique to PAFC, but is not a selected critical component as there are no major changes to the cost or system performance of this component forecast.

Similarly to MCFC, the majority of the supply chain is outside of the Europe. The main markets are in Korea and US with Japanese (Fuji Electric) and Korean (Doosan) companies as the main actors.

As with AFC, little or no direct KBA activity is focused on conventional PAFC. The use of phosphoric acid immobilised in a PBI membrane does have relevant KBAs, but this approach is included as high-temperature PEM under PEMFC.

The rationale for selecting critical components for further examination is similar to AFC: there are a small number of actors and the supply chain tends towards vertical integration.

6.7 MCFC

Molten carbonate fuel cells (MCFC) operate at high temperatures and use a molten carbonate salt as the electrolyte. This electrolyte is suspended in a porous matrix, often made out of lithium aluminium oxide. The high temperature process means that precious metals are not needed to catalyse the reactions and instead metals such as nickel can be used as catalysts on the electrodes. In avoiding precious metals the cost of catalysts is significantly reduced. However, nickel can migrate in the aggressive high temperature conditions of an MCFC having negative effects on the lifetime of the fuel cell.

The high temperature also benefits MCFC technology as a fuel reformer is not required, reducing the cost of the system. Instead MCFC undergoes *internal reforming*, where the temperature converts fuels like natural gas into hydrogen in the cell.

Whilst the reduced cost and efficiency of MCFC make this technology attractive, there are issues over the lifetime of these cells due to the high temperatures and corrosive electrolyte. Further research and development in materials for MCFC technology could mitigate these challenges.

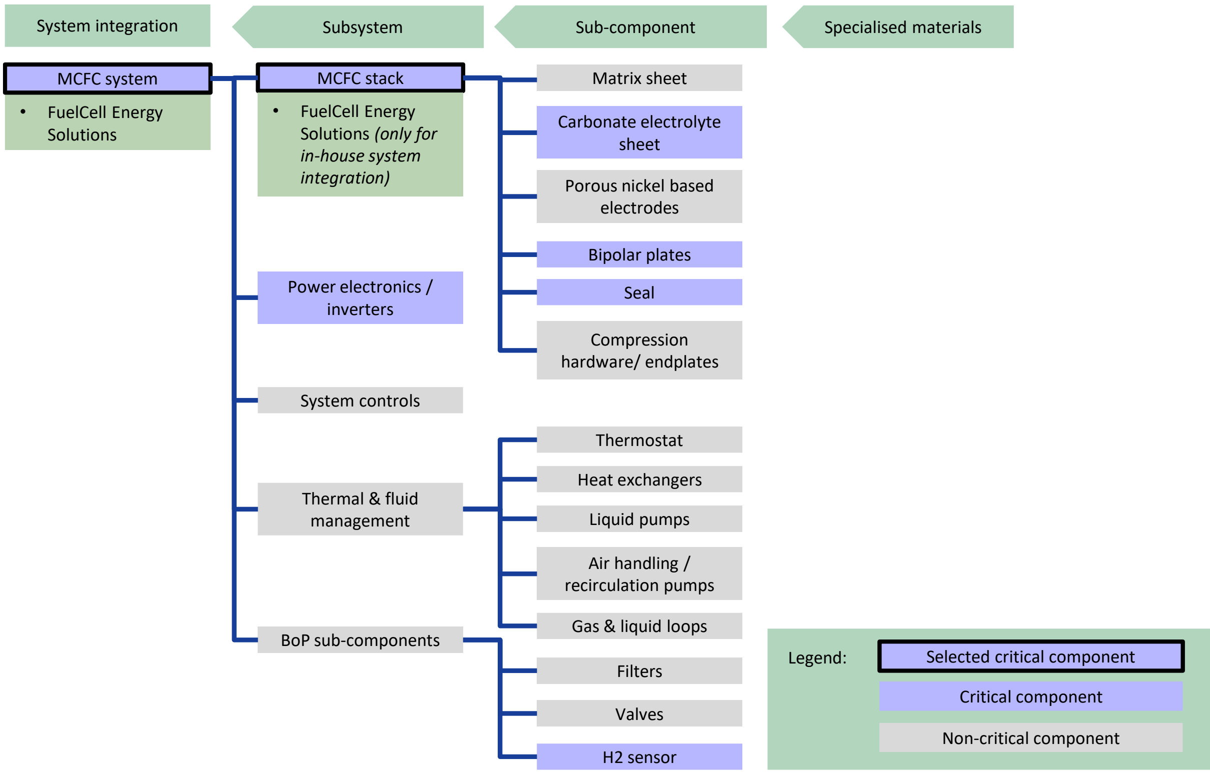


Figure 42: MCFC supply chain structure with European actors in selected critical components

There are very few system integrators in the MCFC technology. In Europe, there has been very little development of MCFC since MTU and Ansaldo exited the technology several years ago. However, FuelCell Energy's JV with Fraunhofer IKTS (FCE-Solutions) does provide system integration, servicing and other support capabilities within Europe. The majority of the supply chain, including components and materials, is located outside of Europe, in North America and to some extent Korea where FuelCell Energy have the majority of their production capacity. Although some KBAs have good skills and relevant accumulated knowledge in the area (Fraunhofer and ENEA for example), little or no work is ongoing.

Selected critical components were restricted to the MCFC stack and system due in part to the tendency towards vertical integration of MCFC manufacturers. This tendency towards vertical integration and the limited number of actors involved leads to a lack of depth or breadth in the supply chain.

6.8 HRS

Hydrogen refuelling stations are a key part in expanding fuel cell transport and in some cases electrolyser deployment. Currently the hydrogen from HRS is delivered at either 350 or 700 bar, where 700 bar is used more for light-duty vehicles with higher pressure tanks designed to minimise the amount of space needed. 350 bar refuelling is mainly directed at HGVs and larger vehicles where space for the tank is less of an issue. HRSs have a very different supply chain structure from the fuel cell and electrolyser technologies. It includes a sub-system for storage, most commonly compressed hydrogen storage. This sub-system is discussed in Section 6.13, where the supply chain for this technology is explained in more detail.

The deployment of HRS in Europe is one of the most developed networks alongside Japan, meaning that the actor landscape in the Europe is generally, and relatively, strong and developed. Active KBAs have skills in specific components of HRS, such as compressors or metering systems, in systems engineering and optimisation, and also in monitoring and analysis. Others have expertise in the design of efficient hydrogen refuelling systems, innovative on-site electrolysers and how these two can most effectively mesh.

The compressors and fuel dispenser/hoses were selected critical components as these tend to be high cost, specialty items undergoing significant testing and development while sensors are included because of continuing efforts to align their function with international codes and standards. Similar to, e.g. stationary CHP, HRS integration and installation is a local endeavour and is included for this reason.

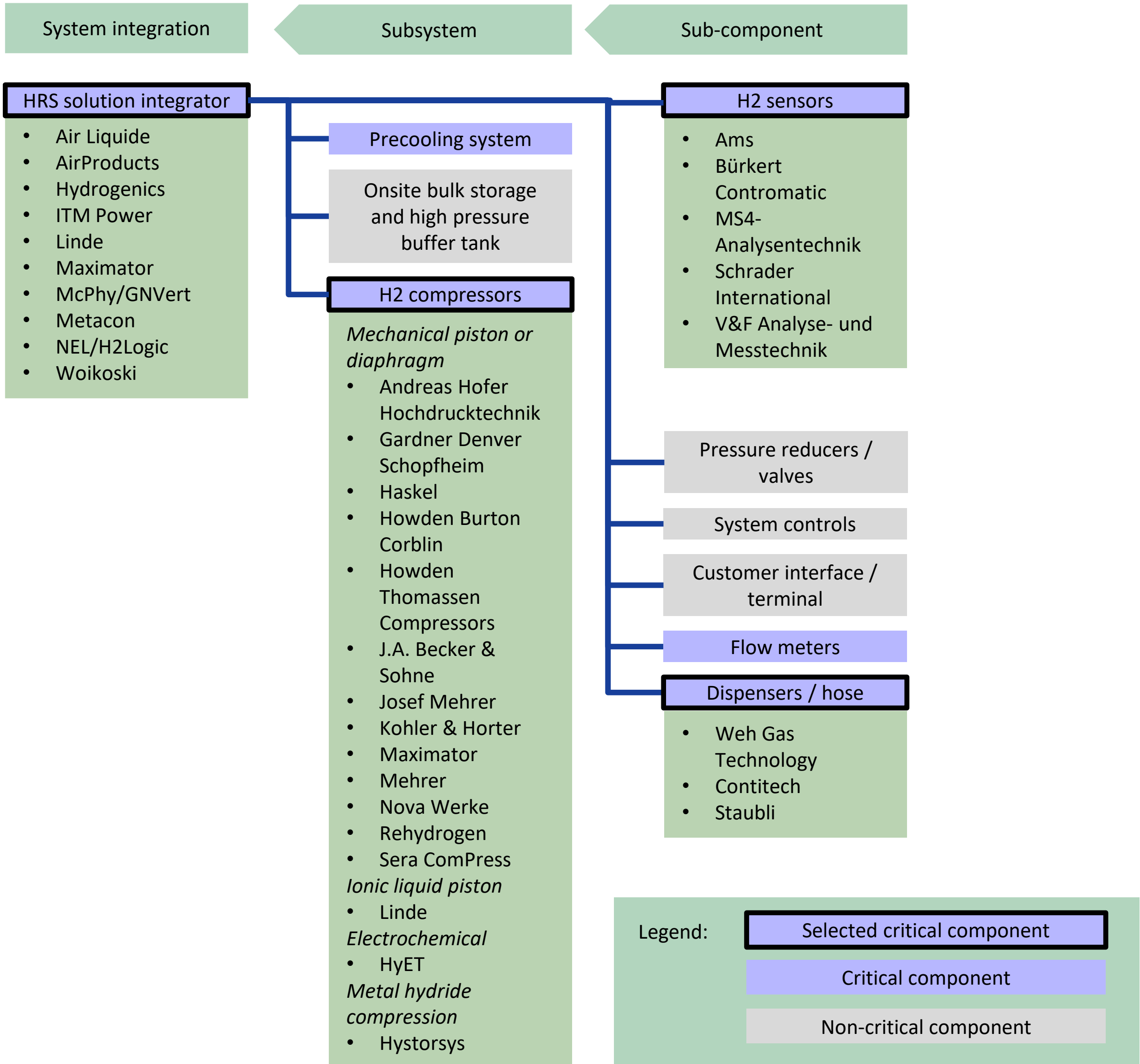


Figure 43: HRS supply chain structure with European actors in selected critical components

Europe is well positioned across most key components in HRS. In addition to onsite production and storage, some important areas include the dispensers and hosing (which is specialised and needs to be certified as withstanding the very cold hydrogen needed for fast filling), valving and flow meters. The main cost component in a refuelling station is the compressor. Dispensers and controls (including metering) are also important cost factors[150] and product availability for HRS applications is currently low.

Some European actors have pioneered the development of new components required for HRS (e.g. the dispenser and hosing). There is still a lack of flow meters that meet the accuracy requirements of weights and measures authorities, but there is relevant development activity by some European actors. Other areas, such as in-line purity assurance, are still an area of R&D activity, also by component developers. In hydrogen compressors Europe has several suppliers to choose from including some that have developed, or are still developing novel compression technologies. The same is broadly true for sensors, where specialist measuring companies exist, some of whom have developed or are developing capabilities in this area. KBAs also play an important role, as novel measurement techniques could significantly reduce cost or improve sensitivity of sensor technologies, or the reaction speed.

Some actors in a single component are increasing their attractiveness to the industry by also offering subsystems. For example, compressor companies developing or acquiring expertise in valves and dispensers.

6.9 Fuel processors / reformers

Fuel processors are a key element in most of the fuel cell chemistries if the input fuel is not pure hydrogen. The level and type of fuel conversion depends on the fuel used, operational temperature of the fuel cell and the fuel type and purity of the fuel needed for the fuel cell, which is typically a hydrogen-rich or near-pure hydrogen gas stream. A variety of fuels can be used to create this hydrogen through the conversion process.

High-temperature fuel cells operate a process known as internal reforming, where the high internal temperatures of the cell mimic some of the process that takes place in a fuel processor. Technologies that can use internal reforming require the desulphurisation of the fuel, and may have a 'pre-reformer' to crack some of the incoming hydrocarbon and help balance the reactions.

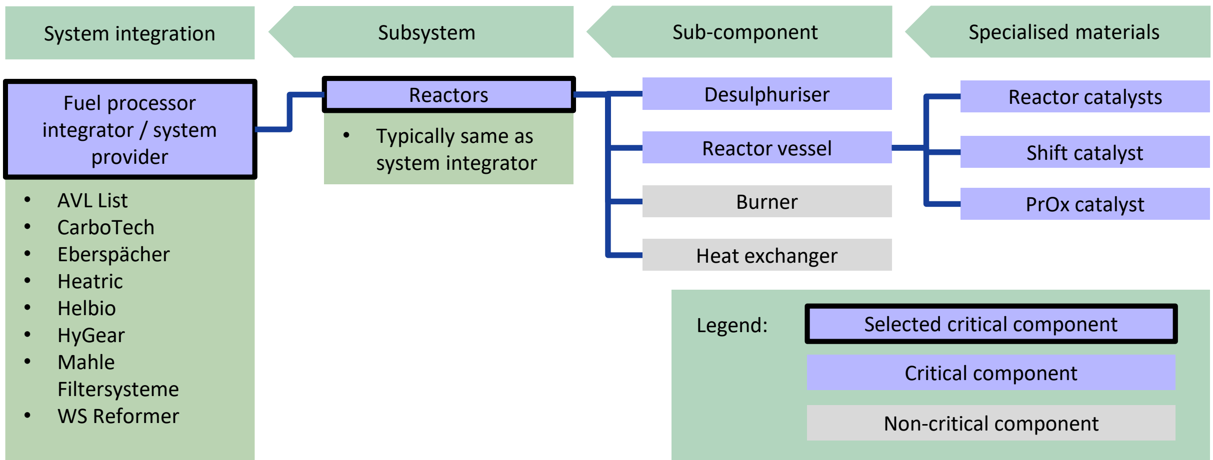


Figure 44: Fuel processor/reformer supply chain structure with European actors in selected critical components

Integration actors in fuel processors often operate across most of the components and supply chain, only purchasing the materials needed for the manufacture of the system. Europe has strong companies for

[150] Argonne National Laboratory - Hydrogen Infrastructure Analysis in Early Markets of FCEVs, IEA Hydrogen Roadmap- North America Workshop 2014. URL: http://www.iea.org/media/workshops/2014/hydrogenroadmap/9anlamgadelgowainy.pdf

integration of fuel processors that are used in many of the fuel cell technologies and a few who produce stand-alone systems.

Europe is also well placed for the specialised materials in the supply chain, with Johnson Matthey, BASF, Umicore and others capable of supplying reaction catalysts.

The reactors are often produced by the system integrator for the fuel processor. All of the components and materials below subsystem level are described as non-critical. The KBAs for fuel processors are described in Section 5.10.2.

6.10 AEL

Alkaline electrolysers transport hydroxide ions through the electrolyte from the cathode to the anode, with hydrogen being generated at the cathode. Alkaline electrolysers use a liquid alkaline solution of sodium or potassium hydroxide as the electrolyte.

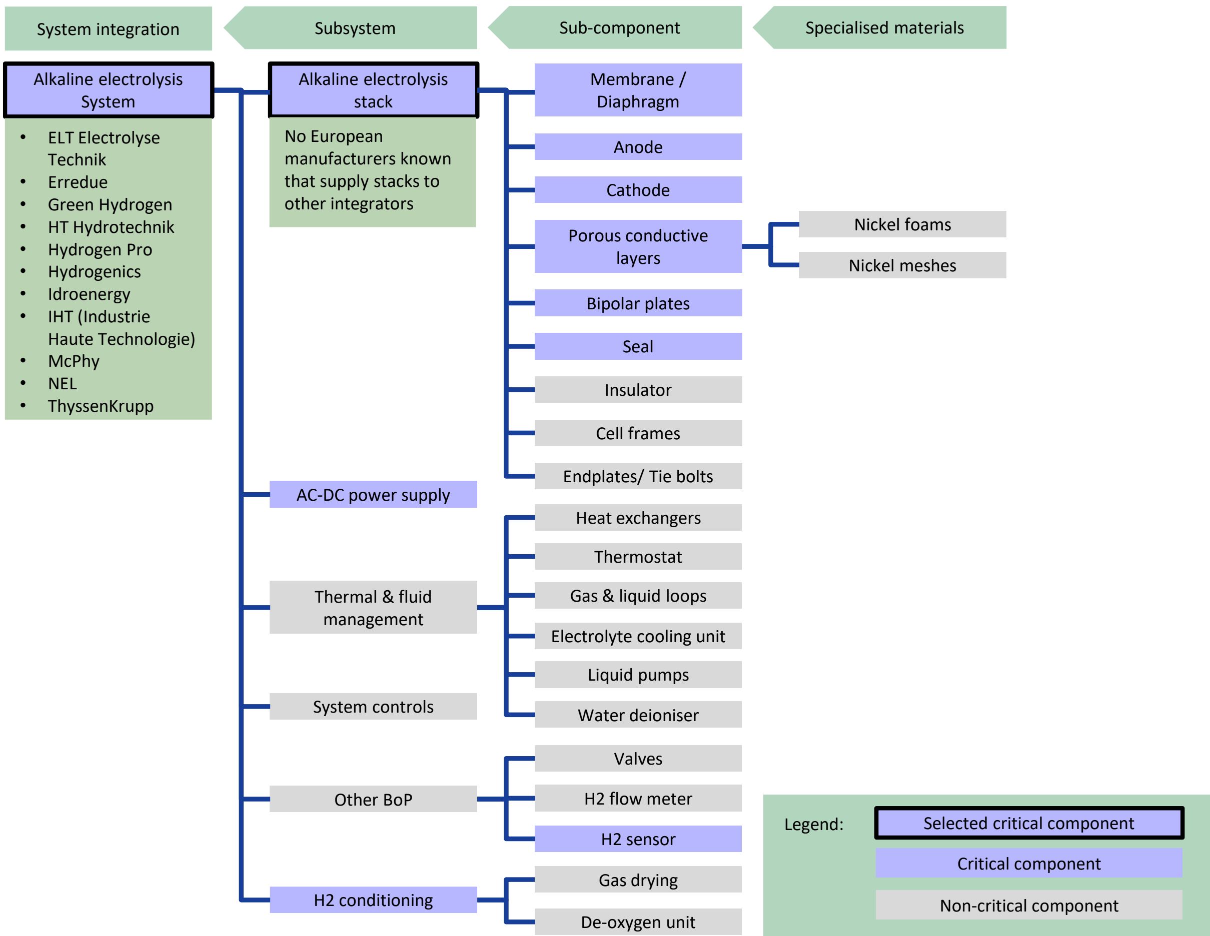


Figure 45: Alkaline Electrolyser supply chain structure with European actors in selected critical components

The supply chain of AEL shares some commonalities with the chlor-alkali electrolysis industry, but the alkaline water electrolysis systems typically deployed today are of much smaller scale, and so is the overall market. Alkaline electrolysers have no particular material or component that stands out in cost or supply risk. Main cost contributors are the cell components including anode and cathode as well as the bipolar plates. The membrane or diaphragm is another major cost contributor. Some system integrators use their own proprietary membrane chemistries, while others source from a few suppliers globally.

The components for alkaline electrolysers can generally be sourced within Europe. Most of the components used in anode, cathode and bipolar plates are more or less standard industrial materials, produced to the specifications of the system integrators. The diaphragm materials are crucial for performance and although standard materials exist, some system integrators use their own proprietary designs. The single largest cost contributor to the system is the stack (50%) followed by the power electronics (15%)[151]. Within the stack, anode and cathode are typically the main cost contributors, while the contribution of the diaphragm and bipolar plates varies depending on design choices.

The AEL stack and system were identified as critical for the value add and deployment analyses. The analysis resulted in no critical components below the stack level, as many of the components are mature and there is little expected technological evolution.

As with PEMEL, AC-DC conversion (the power supply) is a major cost contributor, and this is expected to become even more prominent at higher future production volumes when stack technology itself becomes cheaper. Power electronics components are essential for a very wide range of applications beyond electrolysers. KBAs in Europe are strong in various aspects of AEL technology and systems, from fundamental modelling through materials to system design and integration. Activity has increased as interest in the sector has increased, and many KBAs are globally competitive.

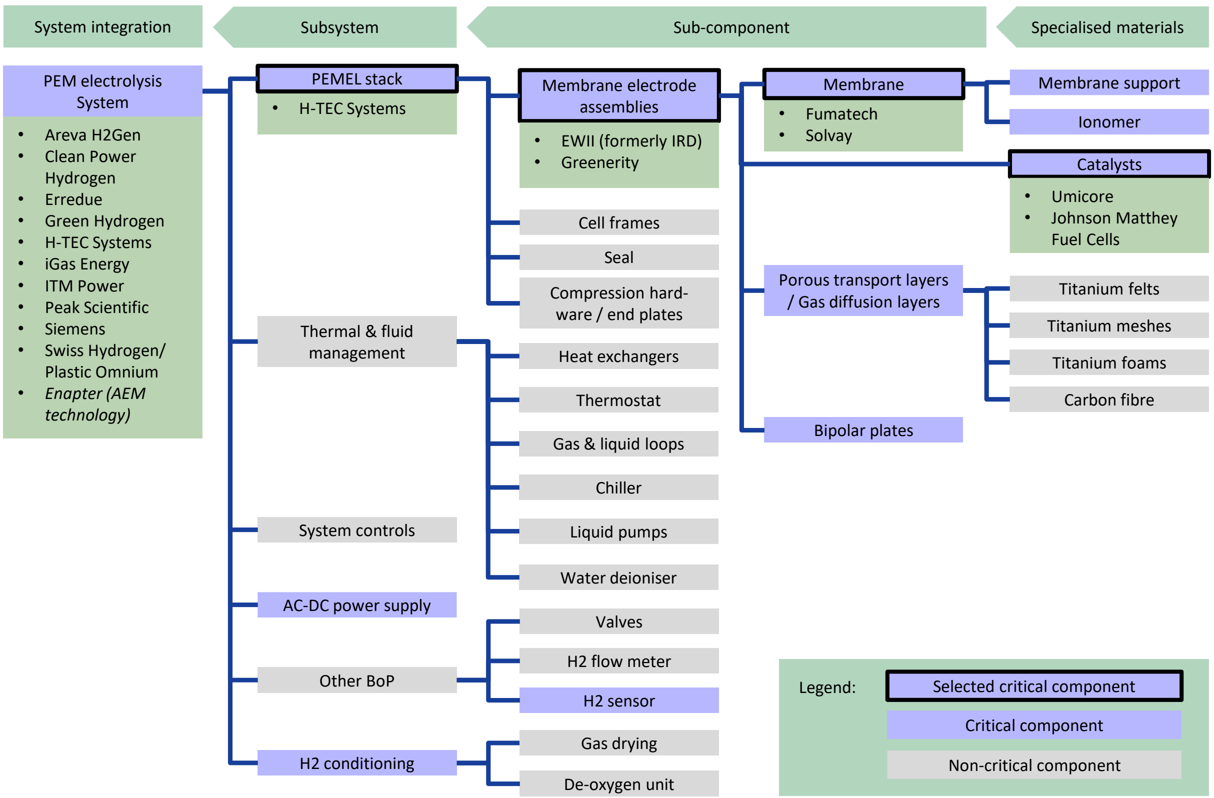


Figure 46: PEM Electrolyser supply chain structure with European actors in selected critical components

6.11 PEMEL

As with fuel cells, the central functional component of PEM electrolysers include an anode and cathode separated by an electrolyte. Water is catalytically split into oxygen gas and hydrogen ions at the anode,

[151] FCHJU Development of Water Electrolysis in the European Union, 2014 (p.36)

hydrogen ions move across the membrane, and then combine with electrons at the cathode to form gaseous hydrogen.

In stack components, PEM electrolysers resemble PEM fuel cells to some extent, though due to the higher voltages, corrosion-resistant materials such as titanium are used, making many components costly. The critical components are generally similar to PEMFC. PEM electrolysis catalyst compositions are different from PEM fuel cells, although the same actors are involved in the electrolyser supply chain. The main cost contributors to the system are the stack (40%-60%), followed by the power electronics (15%-21%)[152]. Within the stack, the core components that drive the cost are the layers of the MEA. Titanium based bipolar plates and meshes are typically used[153].

In recent years, several European developers have started to commercialise their own PEM electrolysers, most of them in view of expected market growth as part of the energy transition. There is little public information on sourcing of components by the system integrators, but many of the supply chain companies currently supplying PEM fuel cell integrators also offer components for PEM electrolysers. This means that Europe is well positioned all along the PEM electrolyser supply chain, however, the electrolyser-specific supply chain is in general less developed compared to PEM fuel cell supply chain.

AC-DC conversion (the power supply) is a major cost contributor, and this is expected to become even more prominent at higher future production volumes when stack technology itself becomes cheaper. Power electronics components are essential for a very wide range of applications beyond electrolysers.

Strong actors also exist in the KBA sector, with crossover expertise from PEMFC activities in materials, catalysis etc, and in system design, engineering and safety from other types of electrolysis and hydrogen systems.

6.12 SOEL

Solid oxide electrolysers use the same principle as SOFC, using a solid ceramic electrolyte that conducts oxygen ion (O^{2-}) at temperatures above 700°C. Water at the cathode combines with electrons from the external circuit to form oxygen ions and hydrogen gas. The oxygen ions move through the electrolyte to the anode, forming oxygen gas and generating electrons for the external circuit. SOEL technologies boast high efficiencies but the high temperatures required for this process to take place results in large energy consumption, especially if this heat is produced solely from electrical sources. SOEL use a solid ceramic as the electrolyte.

[152] Colella et al. 2014 'Techno-economic Analysis of PEM Electrolysis for Hydrogen Production"
https://energy.gov/sites/prod/files/2014/08/f18/fcto_2014_electrolytic_h2_wkshp_colella1.pdf (slide 10)
[153] FCHJU Development of Water Electrolysis in the European Union, 2014 (p.35)

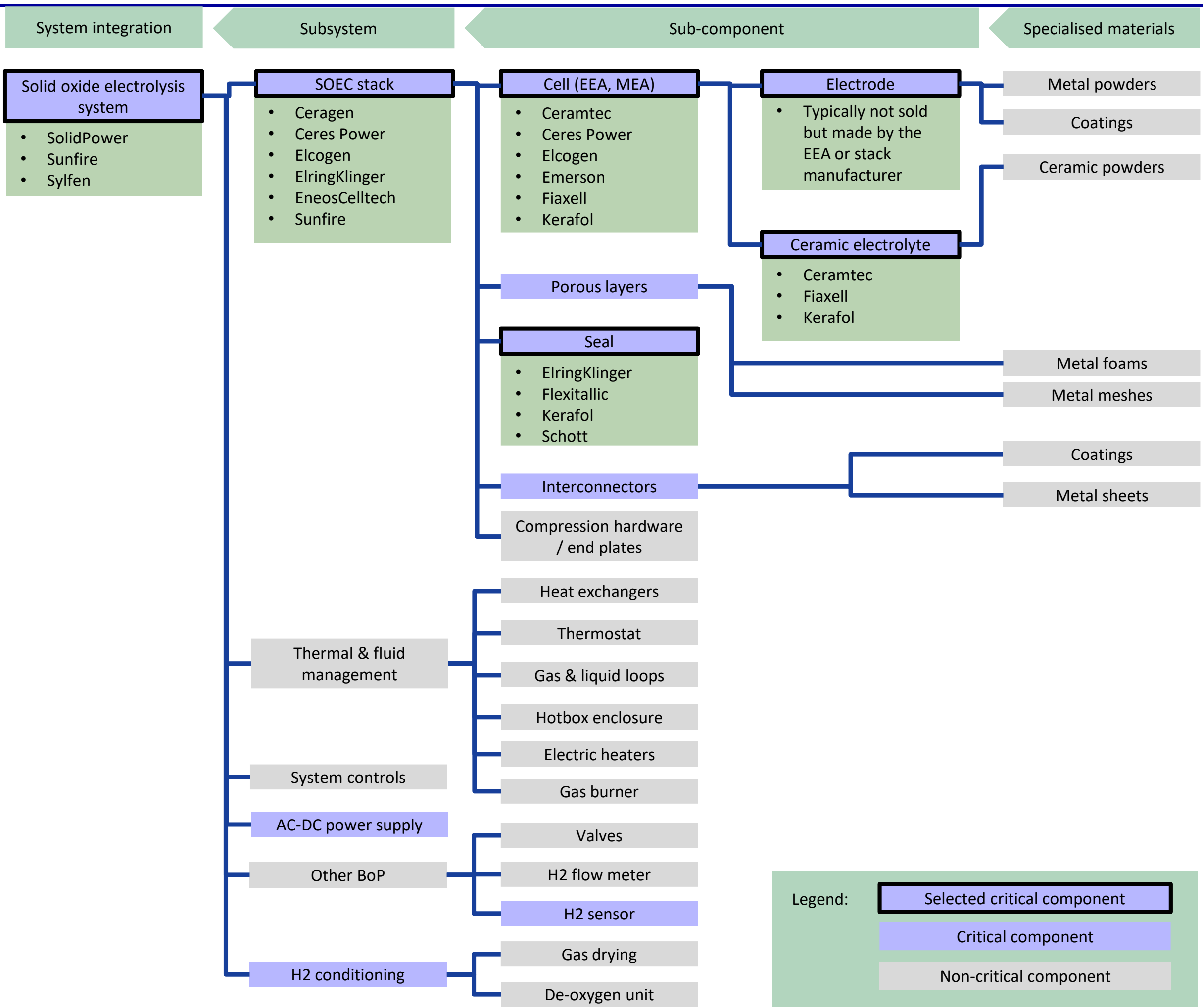


Figure 47: Solid Oxide Electrolyser supply chain structure with European actors in selected critical components

Like PEMFC and PEMEL, the structure of the supply chain for SOEL is relatively similar to that of SOFC. Although hydrogen conditioning steps are used in SOEL and other electrolyser technologies. The components for SOEL at the stack level are largely the same as in SOFC, although less optimisation for electrolyser operation has taken place to date. Due to their similarity, the critical components selection rationale is the same for SOEC and SOFC. Although reliable cost analysis is lacking due to the early stage of commercialisation of the technology, indicative results from published analyses suggests that stack cost contributes about 35% to overall system cost[154]. As with SOFC, the repeat cell layers within the stack are most critical and the highest contributors to overall stack cost.

Similar to SOFC, Europe has a breadth of suppliers and developers with excellent knowledge of the key stack components, and European system integrators can be considered globally leading. Though the technology is only early commercial, and there is a lack of experience with larger volume manufacturing.

KBAs are both active and strong, and typically overlap strongly with actors in SOFC, as the skillsets are almost identical. Europe probably leads globally in this sector.

[154] James et al 2016 'Techno-Economic Analysis: Water splitting technologies and metrics ' https://energy.gov/sites/prod/files/2016/05/f31/fcto_awsm_wkshp_5_james.pdf

6.13 Compressed H2 storage

Hydrogen is often stored at ambient temperatures, compressed to 350 bar or 700 bar. Common pressure vessel capacities for vehicles are is 2.5 and 5 kg, with multiple vessels being used depending on vehicle range and packaging. Hydrogen storage tanks are given a type designation according to the material from which they are made, for instance composite tanks of carbon fibre with polymer linings are designated Type IV. Type III tanks have a metal liner, but are not as common in transportation applications – with the exception of China – due to their higher weight and cost.

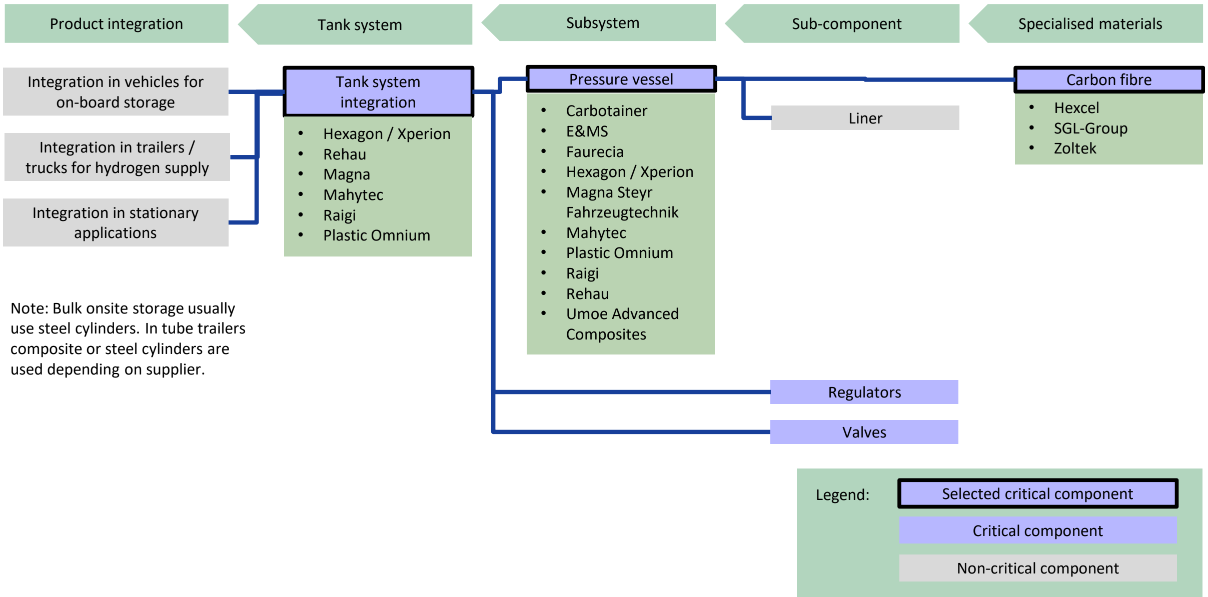


Figure 48: Composite pressure vessel H2 storage supply chain structure with European actors in selected critical components

Europe is well-placed in the compressed hydrogen storage market, with many suppliers and developers. Although compressed storage appears to have many players, not all produce tanks in Europe, and this remains a weakness in the supply chain. Hydrogen compressed tank supply has some strong Asian and North American players, with specialist materials coming more from Asia. Valves and regulators are an important area for cost reduction and good opportunities exist for export, though there are few suppliers generally. Both the regional and the global supply chain need strengthening. Europe does, however, have a base of high-quality balance of plant component suppliers such as OMB Saleri in Italy and Pressure Tech in the UK, which would be well positioned to supply a growing market.

Numerous actors offer pressure vessel technology and it is a globally competitive market, but those offering high pressure for hydrogen applications are limited, and Europe does not have an especially strong position. The engineering and material science underpinning pressure vessel production offers some opportunity for cost reduction and superior products, and this subsystem was identified as a critical component in the analysis. Carbon fibre composites are the structural material used in pressure vessels and are also a critical component. Indeed, carbon fibre is found in many lightweight, high-strength applications, and European and North American competition with Japan to develop domestic low-cost high and medium modulus carbon fibre is an ongoing concern. Strong KBAs exist with relevant skills in this category, including materials, modelling, safety and production engineering. Other regions, including both N America and Asia, have equal or greater capabilities however.

7 Critical components

7.1 Introduction

The detailed results from the analysis of the critical components through the methodology discussed in Section 2.5 are included in this section, split by component. A description of the critical components and relevant information is included, along with a SWOT analysis for each. Only strengths, weaknesses, opportunities or threats related to the European supply chain for the component (equivalent to those in **black bold text** for the application as a whole) are given. Strengths, weaknesses, opportunities or threats related to the conditions for deployment of the application (**blue bold text** in the earlier SWOTs) are not relevant at the component level.

The components and subsystems exist at different levels of technical, commercial and manufacturing readiness. Ideally, these levels would be applied to the different components to indicate their status and help to identify gaps and bottlenecks which might be resolved through different measures. Unfortunately, very limited data are available on where current components and systems sit within these specific levels, for several reasons:

- In some cases the levels are commercially sensitive, so the actors who have insight into the exact status of a component are not willing to reveal it;
- A component may exist in a mature form, but in an obsolete technology. For example, hundreds of thousands of MEAs of certain types have been manufactured, but the next iteration of the technology uses different compositions or materials and so the readiness level has dropped back even as the technology advances;
- Technology, commercial and manufacturing readiness level are closely intertwined. A component may have achieved manufacturing maturity in one form, but in order to improve performance or reduce cost both the component and the manufacturing technique may require modification, retarding their readiness level.

Because of this the readiness levels are not reported below. In general, FCH components are at technology readiness levels just below full commercial exploitation, with cost the primary issue still to be managed. Manufacturing readiness levels are similar, with the caveat that very high speed, high yield manufacture has not been demonstrated or implemented in most cases. Commercial readiness levels are held back by cost, and so are also below full commercial status.

7.2 Fuel cell stack integration

7.2.1 PEMFC, DMFC and SOFC stacks

A robust and well-functioning fuel cell stack is essential in any system, and while it is composed of many elements, the integration of the stack involves deep expertise and know-how in addition to analytical capabilities. While increasingly the know-how is transferable, successful stack integration is also dependent on the components used and so stack integrators tend to have at least some specialised component requirements, for example in the design of the bipolar plate. In SOFC the stack integration is even more individual, and depends not only on component design but also on materials sets. Pure-play European stack integrators – i.e. those who are not system or application developers – include PowerCell, Proton Motor and Intelligent Energy in transport (PEMFC), and Ceres Power and Solidpower in stationary (SOFC). Larger entities such as Daimler (for transport PEMFC) and Viessmann (stationary SOFC) have in-house capabilities but have also relied on external or acquired stack specialists for their PEMFC system.

Because the stack integration is so closely related to the final application integration, the SWOT analyses for this step in the value chain are the same as those for the applications described in Section 5 and are not repeated here. In PEMFC, DMFC and SOFC, individual cells (MEA, EEA) are preassembled before being stacked together. These intermediate components are discussed in more detail in 7.7 (PEMFC and DMFC) and 7.8 (SOFC). In the AFC, PAFC (not the PBI membrane concepts included as High Temperature PEMFC [155]) and MCFC chemistries, preassembling electrode-electrolyte sub-assemblies is uncommon, and instead the layers are brought together directly to build up the stack. Therefore the stack integration for these is detailed in the following subsections.

7.2.2 AFC stack

7.2.2.1 Description

An AFC stack producer has a choice of whether to use base metal catalysts (such as nickel) or precious metal catalyst to coat the electrodes. This choice is a trade-off between the higher performance of precious metal catalysts and the lower cost of base metal.

The AFC stack is made up of the porous layers – which are simple mesh structures, electrodes, bipolar plates and an electrolyte. The electrodes consist of a supporting conductive substrate structure and catalyst coatings. The integrators producing the stacks have the ability to buy the materials for the electrode in powdered form and process the electrodes themselves. Some AFC cell designs use membranes like those in the chloro-alkali industry to let through OH ions. This can improve the equilibrium of reaction by reducing concentration gradients in the electrolyte. Tyvek is often used for the membrane. The electrolyte used is almost always potassium hydroxide. Sodium hydroxide is being investigated but has issues still to be resolved.

AFC technology is produced by very few companies – AFC Energy (UK) and GenCell (Israel). These system integrators operate throughout the *ad-hoc* supply chain, producing their own AFC stack and often the sub-components, from purchased materials.

7.2.2.2 SWOT

A SWOT analysis at critical component level for AFC stack. This SWOT focuses on the technical capabilities of European companies in each component.

Table 74: SWOT of European AFC cell capabilities

STRENGTHS	**WEAKNESSES**
• Europe has a leader in AFC technology (AFC Energy) although its products are not yet commercial	• Lack of investment in AFC technology • Very limited commercial roll-out means market is still uncertain • Little or no R&D is carried out specifically on AFC in KBAs as the market is so small currently

[155] PAFC designs based on PBI membranes work through the encapsulation of phosphoric acid as the ion conductor and are commonly referred to as 'high temperature' PEM, and are included under PEMFC.

OPPORTUNITIES	THREATS
• AFC technology may establish a strong place in the market over time due to its relatively low capital cost	• AFC technology may be displaced by other FC types

7.2.3 PAFC stack

7.2.3.1 Description

PAFC stacks are made of a matrix that allows the movement of the phosphoric acid electrolyte. The chemistry of PAFC technology requires precious metal catalysts. Therefore, the constituent parts of the PAFC stack are the matrix, flow field/bipolar plates and the catalysts. The largest actors in PAFC are not based in Europe, with production and integration mainly happening in the US, Korea and Japan.

7.2.3.2 SWOT

A SWOT analysis at critical component level for PAFC stacks. This SWOT focuses on the technical capabilities of European companies in each component.

Table 75: SWOT of European PAFC cell capabilities

STRENGTHS	WEAKNESSES
• PAFC matrix type fuel cell components are produced in Europe for export	• No producers of PAFC stacks in Europe • The dominant players are in Asia and may try to develop local capability
OPPORTUNITIES	**THREATS**
• Doosan is increasing manufacturing capacity and so demand for cells could increase	• The largest producer, Doosan, operating in the US and Korea has established a large market share for commercial and large scale PAFC CHP systems which is a deterrent to new European entrants • Existing European manufacture could relocate to regions where market demand is higher • Other FC types could prove more competitive, taking market share from PAFC or making it obsolete

7.2.4 MCFC stack

7.2.4.1 Description

Similarly to AFC, there are only a few players in MCFC and the system integrator tends to develop their own stack technology. The cell takes a different structure with a ceramic matrix being used instead of a membrane like in some other chemistries. Molten carbonate salt passes through this matrix acting as the electrolyte. The high operating temperatures and the chemistry of these cells means that no precious metal catalyst is needed. MCFC technology is only produced for large-scale primary power and CHP fuel cell applications.

The cells of the stack are made up of various specialised components. The ceramic matrix, also known as the electrolyte tile, is commonly made up of porous Lithium aluminate ($LiAlO_2$) and uses an electrolyte that is a made up of lithium and potassium carbonates (Li_2CO_3 and K_2CO_3) in a two-third to one-third split, respectively. The semi-solidness of the matrix makes it impermeable to gas and provides a gas-tight seal through what is known as a 'wet seal'. This takes the role of a gasket and allows the seal to be formed between the matrix and the cell-housing. This 'wet seal' only works for metallic cell housings; if ceramics are used for structure then conventional seals are required[156].

The cathode and anode in a MCFC cell are commonly made up of porous lithiated nickel oxide and porous nickel-chromium alloys, respectively. Nickel oxide has soluble properties and therefore limits the lifetime of cathode and fuel cell, leading to other materials being explored for this component. The anode can also use other metals, such as cobalt and copper in a powdered alloy or composite with oxide form, with additives of chromium or aluminium to increase the long-term stability[156].

7.2.4.2 SWOT

A SWOT analysis at critical component level for MCFC stack. This SWOT focuses on the technical capabilities of European companies in each component.

Table 76: SWOT of European MCFC Cell capabilities

STRENGTHS	WEAKNESSES
• One company with manufacturing capabilities	• No companies currently producing in Europe
OPPORTUNITIES	**THREATS**
• Growth of European demand for large-scale fuel cell CHP could possibly see manufacturing scale-up of MCFC technology in Europe	• Other FC chemistries could displace MCFC

7.3 Electrolyser stack integration

7.3.1 Description

As is true with fuel cells, the integration of the electrolyser stack requires know-how and deep expertise, and so is a critical point in the value chain. Again, however, some of the requirements and skills are somewhat specific to individual technology choices and designs. Stack integrators will also have specific component design and performance requirements. Europe is very well placed in alkaline stack integration, with companies such as Hydrogenics and Nel, and in PEM stacks, through players like ITM Power and Siemens. Europe arguably leads globally in SOEL, with Sunfire a leading proponent, though systems in general remain to be proved. Unlike some players in fuel cell stacks, most electrolyser stack integrators are also system integrators. Because the stack and system integration is therefore largely the final application integration, the SWOT analyses for this step in the value chain are the same as those for the applications described in Section 5 and are not repeated here.

7.4 Pressure Vessel

7.4.1 Description

A composite pressure vessel is a critical component in the compressed hydrogen storage application, as is the carbon fibre used to wind the vessel (discussed in Section 6.13). Hydrogen is typically stored at ambient temperatures, compressed to 350 bar or 700 bar. Pressure vessel capacity varies by application, with FCEV

[156] Blomen, L.J.M.J. and Mugerwa, M.N. (1993) 'Fuel Cell Systems'. Chapter 9, pp 350.

typically using 5 kg storage tanks. Pressure vessels are given a type designation according to the material(s) from which they are made, for instance composite tanks of carbon fibre with polymer linings are designated Type IV. Most vessels used in transport are this type, though in China they are not certified and Type III (metal liners with composite windings) are used. Fully composite tanks (Type V) are in development. The vessels are relatively high cost, as the materials are also specialised and in high demand, while the current manufacturing processes can only be scaled by increasing the number of machines, which is bulky and limits the benefit.

7.4.2 SWOT

The SWOT analysis for pressure vessels as a critical component focuses on the technical capabilities of European companies.

Table 77: SWOT of European pressure vessels capabilities

STRENGTHS	WEAKNESSES
• Some companies already manufacture and deliver pressure vessels • Interest is increasing and new actors are developing technology capability	• The supply chain is not well secured, with aerospace dominating upstream demand • Non-European companies dominate pressure vessels for transport • Costs remain high, and supply is limited
OPPORTUNITIES	**THREATS**
• Heavy-duty markets look set to grow, with requirements for potentially large numbers of tanks • Supply is limited globally so export opportunities exist	• Companies in other regions have greater capacity and incumbency, so European industry may not be able to grow • Regulations can be used to block companies from certain markets, as is the case in China to some extent

7.5 H2 Compressors

7.5.1 Description

Hydrogen (H_2) compressors are usually required for HRS applications. They may take hydrogen at the relatively low pressures after it is produced (20-30 bar) and increase the pressure for storage on board hydrogen fuel cell vehicles, or be used within a cascade filling structure to boost pressure. These pressures are usually 350 or 700 bar. There are various types of H2 compression technologies and these are[157]:

- Mechanical
- Ionic liquid piston (analogous to mechanical but with some technical advantages)
- Electrochemical
- Metal hydride

European companies are developing novel H_2 compressor technologies including electrochemical and metal hydride-based processes, but these are not fully commercial. Gas compression technology is mature but requirements for HRS and other hydrogen applications are more difficult to meet reliably than conventional industrial applications, and so innovation is ongoing.

[157] DoE (Accessed June 2018) 'Gaseous Hydrogen Compression

7.5.2 SWOT

A SWOT analysis at critical component level for H2 compressors. This SWOT focuses on the technical capabilities of European companies in each component.

Table 78: SWOT of European H2 compressors capabilities

STRENGTHS	WEAKNESSES
• Europe has a wide range of established compressor manufacturers • European companies and KBAs are developing novel and potentially competitive technologies • European companies export globally	• Few European companies focus on HRS grade compressors • Companies from other regions are strongly positioned
OPPORTUNITIES	**THREATS**
• Current compressors are relatively high cost and reliability can be poor, so alternative solutions could succeed • Significant HRS growth is expected so markets could grow substantially	• New entrants, novel technologies or lower-cost compressors from other regions could capture market share

7.6 Reactors

7.6.1 Description

The reactor refers to the main part of a fuel processor/reformer that transforms the fuel into the hydrogen needed for the fuel cell to work uninhibited. A fuel processor is used for PEMFC, SOFC, PAFC and AFC technologies when these are fuelled with natural gas for instance. The production of reactors is almost always carried out by the integrator of the fuel processor. This is true for almost all of the supply chain for fuel processors, except for the catalyst materials.

7.6.2 SWOT

A SWOT analysis at critical component level for reactors. This SWOT focuses on the technical capabilities of European companies in each component.

Table 79: SWOT of European reactors capabilities

STRENGTHS	WEAKNESSES
• Europe has good specialised engineering capabilities in reactors • Europe’s KBAs are strongly placed in analytical and optimisation techniques	• Other regions, especially Asia, are very strong in reactor development and manufacturing • Costs in other regions can be considerably lower than Europe

OPPORTUNITIES	THREATS
• Hydrogen requirements are growing and so market opportunity is expected to grow	• Asian companies are well-placed to expand their offering and compete more strongly in Europe • Electrolysis or other production methods could out-compete fuel processing technology

7.7 PEM MEA

7.7.1 Description

The PEM MEAs are the constituent cells of a PEM fuel cell stack. The MEA is made up of the polymer electrolyte membrane, catalyst, GDL and flow field/bipolar plates, with only the latter not also resulting in critical component status. Although, in transport applications coated plate materials are used in the bipolar plates and these have a critical evaluation. PEM MEA are required in all PEMFCs and therefore span all applications associated with PEMFC, stationary and transport.

7.7.2 SWOT

A SWOT analysis at critical component level for PEM MEA. This SWOT focuses on the technical capabilities of European companies in each component.

Table 80: SWOT of European PEM MEA capabilities

STRENGTHS	WEAKNESSES
• Europe has one of the top two producers of MEAs in the world, Johnson Matthey, for PEMFC, DMFC and PAFC technologies • Europe has established producers of all the sub-components of the MEA • Europe has strong KBAs developing novel materials and approaches • Local demand for MEAs is reasonably strong, which supports development • MEAs are also exported globally	• Most demand is in transport which is not European-based • MEAs are not yet a major proportion of business activity and so activity is subject to regular Board review
OPPORTUNITIES	**THREATS**
• Chinese desire for JVs and technology transfer could be exploited by EU companies to develop larger export markets • Markets in general are growing and offer good opportunities for leading players	• Both technology and manufacturing capability is being developed elsewhere and will be a competitive threat • China is building strong capability and has the potential to supply at competitive cost • One or two major players leaving the market for strategic reasons could significantly weaken supply options for the whole sector globally

7.8 Ceramic layers for solid oxide fuel cells and electrolysis

7.8.1 Description

Ceramic layers refers to the electrolyte that is used and highlighted as a critical component in SOFC and SOEL technology. SOFC are only used in stationary applications, in particular there are large amounts of SOFCs in operation and being produced for micro-CHP.

7.8.2 SWOT

A SWOT analysis at critical component level for ceramic layers. This SWOT focuses on the technical capabilities of European companies in each component.

Table 81: SWOT of European ceramic layers capabilities

STRENGTHS	**WEAKNESSES**
• Europe has deep industrial and research expertise in ceramic technologies, especially in fuel cells and electrolysers • Several European actors are already engaged in supplying these components locally and internationally • Europe has number of start-up companies with promising technology in SOFC, providing possible markets • Europe has a leader in SOEL technology (Sunfire)	• Europe has no players with significant commercial sales in SOFC • The majority of supply is from companies outside of Europe, especially in Asia • Capabilities are often focused on a specific design or requirement and so demand may depend on very few customers
OPPORTUNITIES	**THREATS**
• SOFC and SOEL markets are expected to grow globally, offering increased opportunities for component suppliers	• Non-European competitors dominate market share and secure their position due to economies of scale etc • Chinese suppliers are well placed because of access to raw materials and low local costs • Novel materials development displaces existing requirements and know-how

7.9 H2 Sensor

7.9.1 Description

Hydrogen sensors are needed in the BoP systems of fuel cell and electrolyser technologies where hydrogen may leak. In this study H2 sensors are only classified as critical components for HRS but not for fuel cell and electrolyser applications.

7.9.2 SWOT

A SWOT analysis at critical component level for H2 sensors. This SWOT focuses on the technical capabilities of European companies in each component.

Table 82: SWOT of European H2 sensors capabilities

STRENGTHS	WEAKNESSES
• Europe plays a leading international role testing and developing advanced hydrogen sensors at the Joint Research Centre Institute for Energy and Transport (JRC-IET), and at some other actors	• No apparent weaknesses
OPPORTUNITIES	**THREATS**
• European investment in hydrogen infrastructure could lead to a large market, fostering domestic production • Leading international R&D role could lead to advanced, domestically produced sensors	• Hydrogen sensors may by highly exportable due to their relatively small size.

7.10 Dispensers/Hose

7.10.1 Description

Some European actors have pioneered the development of new components required for HRS (e.g. the dispenser and hosing). Dispensers and hoses are a critical component of HRS technology, used in the dispensing of hydrogen. They can be adapted to look and feel similar to existing gasoline dispensers, and are produced to meet appropriate standards surrounding safety, leakage, etc.

7.10.2 SWOT

A SWOT analysis at critical component level for dispensers and hoses. This SWOT focuses on the technical capabilities of European companies in each component.

Table 83: SWOT of European dispensers and hoses capabilities

STRENGTHS	WEAKNESSES
• One of the few global suppliers of fuelling nozzles is a European company • Strong engagement by European industrial gas suppliers • Multi-industry development programmes in advanced fuelling strategies, cryogenic and cryo-compressed for example	• Competition from Japan and North America
OPPORTUNITIES	**THREATS**
• If the HRS market expands, Europe is well-positioned to be a major supplier	• Developing supplier bases in Asia and North America

7.11 Polymer Electrolyte Membranes

7.11.1 Description

Polymer Electrolyte Membranes are critical components in all PEMFC applications, in DMFC and in PEMEL. They are usually produced by casting perfluorosulfonic acid-based ionomers into membranes of various thicknesses. During the casting process, there is the option to include inert reinforcing material such as ePTFE and electrospun fluoropolymer fibers to enhance their mechanical strength. Their key feature is the ability to allow the passage of protons and water molecules but to provide a barrier to hydrogen and oxygen gas molecules. The protons are driven across the membrane by a potential difference between the anode and cathode of the cell. Water within the membrane is necessary to achieve the required levels of proton conductivity.

Proton exchange membranes are subsequently coated with (usually) precious metal catalysts to promote the dissociation of hydrogen molecules into protons on one side and the combination of protons with oxygen to produce water on the other. Their properties are key to the performance and lifetime of PEMFC and PEMEL.

The readiness levels of this critical component are detailed in the table below.

7.11.2 SWOT

A SWOT analysis at critical component level for Polymer Electrolyte Membranes. This SWOT focuses on the technical capabilities of European companies in each component.

Table 84: SWOT of European Polymer Electrolyte Membranes capabilities

STRENGTHS	WEAKNESSES
• Europe has a producer of the ionomer raw material (Solvay) which mitigates dependence on imports from US, Japan and China • Europe has producers of membrane for use in-house (Johnson Matthey) and for sale to third parties (Fumatech, Solvay)	• Imports of membrane make up most of market – from US (WL Gore and DuPont) and Japan (Asahi Glass) • There are limited producers of ionomers globally and the barriers to entry to this business are high due to the corrosive nature of the fluorine chemicals involved and the concomitant high safety standards and certification. Only one producer is in Europe and membrane producers have limited purchasing power. • Europe does not have an established producer of expanded PTFE reinforcement material suitable for this application. European membrane producers rely on imports from the USA (Donaldson, WL Gore)

OPPORTUNITIES	THREATS
• Companies can grow with the market from existing strong base	• Development of membranes for PEMFC and PEMEL applications has been focussed in North America and Japan – These companies have a technology and scale (cost) advantage that is likely to be a barrier to growth of existing and new membrane producers in Europe. • Further cost advantages may be achieved by moving production to China where demand is growing rapidly. • China also has end-to-end production capability from fluorspar mine to chemical company, which could reduce production cost

7.12 Gas Diffusion Layer (GDL)

7.12.1 Description

The GDL is an important part of the MEA and a critical component in PEM, PAFC and DMFC technology and all its applications. The GDL, which is usually a carbon fibre paper or fabric serves two main roles: its porous properties allow the transfer of substances like hydrogen and water, as well as heat; the GDL is conductive and allows the transfer of current from electrode to the bipolar plate. In addition, GDLs provide structural support to the MEA as a whole. The GDL is specifically important for liquid handling in PAFC and DMFC. The GDL in PEMEL is not a critical component for the technology.

7.12.2 SWOT

A SWOT analysis at critical component level for GDLs. This SWOT focuses on the technical capabilities of European companies in each component.

Table 85: SWOT of European GDL capabilities

STRENGTHS	WEAKNESSES
• Companies are established in the production and technology of carbon fibre sheet materials and the thermal treatment needed to produce GDLs with high electrical conductivity • Europe has existing strong and specialised GDL suppliers who export globally	• The process for producing GDLs is very energy intensive and the energy cost for European producers is higher than for some producers in North America • The raw material chain for GDLs relies on specific supply options and is not very robust
OPPORTUNITIES	**THREATS**
• The GDL market could grow rapidly with FC commercialisation • Companies can grow with the market from existing strong base	• North American producers could capitalise on low energy costs to take market share from producers in Europe • GDL-free fuel cells are being considered, though these are at an early stage

7.13 High Temperature Seals

7.13.1 Description

High temperature seals are required for MCFC and SOFC technologies. These technologies are relevant to stationary applications.

The main types of seals produced for high-temperature fuel cells, like MCFC, are:

- Bonded seals
- Compressive seals.

Bonded seals are usually glass or ceramics that have a melting temperature close to the operating temperature of the (650°C to 800°C), so that the material softens and forms a tight seal. This type of seal is low-cost and easy to manufacture and apply. However, their disadvantages include brittleness and cell degradation due to the migration of silica in the glass[158].

Compressive seals are elastic over the operating temperature range and soft to fill the roughness of the surfaces that need to be sealed. Although there is difficulty in finding materials that operate in the temperature ranges required. Pressure is required to keep stack components together so a load-frame is needed that is bulky and expensive to implement. Examples for compressive seals are mica and hybrid-mica seals. These materials can withstand high thermal cycling but have high leak rates. Leakage can be minimised by the addition of a thin layer of glass on either side of the seal[159].

7.13.2 SWOT

A SWOT analysis at critical component level for high temperature seals. This SWOT focuses on the technical capabilities of European companies in each component.

Table 86: SWOT of European high temperature seals capabilities

STRENGTHS	WEAKNESSES
• Multiple European actors supplying speciality, high-temperature, ceramic materials • Robust European market for high temperature fuel cells and electrolysers supporting domestic market	• No apparent weaknesses
OPPORTUNITIES	**THREATS**
• As the high temperature FC and related markets grow, specialist material demand will increase	• While high temperature seals are a significant technical challenge, the system market size may not be large enough to entice significant investment in production from large, European specialty materials suppliers.

[158] Spiegel, C. (2017) 'Fuel Cell Gaskets, Spacers, and End Plates'. Fuel Cell Store Blog. Available at: http://www.fuelcellstore.com/blog-section/fuel-cell-gaskets-spacers-and-end-plates

[159] Spiegel, C. (2017) 'Fuel Cell Gaskets, Spacers, and End Plates'. Fuel Cell Store Blog. Available at: http://www.fuelcellstore.com/blog-section/fuel-cell-gaskets-spacers-and-end-plates

7.14 Supported Catalyst

7.14.1 Description

The supported catalysts are a critical component in PEMFC, PEMEL (where unsupported catalysts are also used), DMFC and PAFC technologies. The catalyst is either applied to the gas diffusion layer for support, making an electrode (DMFC and PAFC), or it is applied directly to the surface of the proton exchange membrane to make a catalyst-coated membrane or CCM (PEMFC and PEMEL). It enhances the electrochemical reactions taking place within the cell. The choice of catalyst depends on the fuel cell type, the fuel to be used and the requirements of the application. The majority of catalysts consist of very fine platinum particles dispersed over the surface of a fine carbon powder but in the case of DMFC and when reformate gas containing CO is used in PEMFC and PAFC, some ruthenium is mixed in with the platinum. The catalysts are critical components because they strongly contribute to determining the performance and the lifetime of the cell. Their precious metal content means that they are costly, and a lot of work has been done to reduce the amount of precious metals required without reducing performance. Globally, three leading players supply most of the market. Europe has two of these main actors, Johnson Matthey and Umicore. Tanaka in Japan is the third.

7.14.2 SWOT

A SWOT analysis at critical component level for supported catalysts. This SWOT focuses on the technical capabilities of European companies in each component.

Table 87: SWOT of European supported catalysts capabilities

STRENGTHS	**WEAKNESSES**
• European companies have a significant market share in a market with significant barriers to entry requiring access to and expertise in processing precious metals • Johnson Matthey uses some of its catalyst production in-house in its own MEAs which secures a significant share of the market. • Europe has a capable supplier of the carbon powders required for fuel cell applications	• JM makes some of its fuel cell catalysts in the USA
OPPORTUNITIES	**THREATS**
• JM could decide to make more of its catalysts in its European facilities	• Increasing demand for fuel cells in Asia may be beneficial to Tanaka of Japan, as they have a more established supply position in the region • JM could decide to make more of its catalysts in its USA facility • There are established, capable suppliers of carbon powders in N. America and Japan which could increase their market share based on strong growth of fuel cells in those markets.

7.15 Carbon Fibre

7.15.1 Description

The material carbon fibre is required for forming pressure vessels in compressed H2 storage and also for producing GDLs. However, carbon fibre is only considered as a critical component for the compressed hydrogen storage application. Although the GDL in PEMFC is a critical component of which carbon fibre is a component, the type and quality are completely different to that used in compressed storage and so the supply chains only loosely overlap.

7.15.2 SWOT

A SWOT analysis at critical component level for carbon fibre. This SWOT focuses on the technical capabilities of European companies in each component.

Table 88: SWOT of European carbon fibre capabilities

STRENGTHS	**WEAKNESSES**
• SGL carbon is one of the leading suppliers of carbon fibre • Europe has strong domestic carbon fibre and acrylonitrile production, around 50% of the global capacity.[160] • Europe is a net exporter of acrylonitrile raw material. • Close relationships between domestic carbon fibre production and consumers (e.g. BMW/SGL)	• Japan holds a dominant position in both price and performance, which will be difficult for European companies to compete with.
OPPORTUNITIES	**THREATS**
• FISIPE, recently acquired by SGL, has been developing a lower cost carbon fibre precursor based on textile-grade polyacrylonitrile manufacture. If successful, this has the potential to disrupt Toray's dominant position. • European carbon fibre consumption is strong across many applications (automotive, aerospace, wind)	• Toray, headquartered in Japan, holds a dominant position in the carbon fibre market. • Toray is vertically integrated maintaining tight control of all aspects of the supply chain leaving little opportunity for outside companies to gain access as a supplier or consumer of high quality polyacrylonitrile precursors. • Europe is a net importer of carbon fibre, around 40% of global production.

160 Das, Sujit, Josh Warren, Devin West, and Susan M. Schexnayder. "Global Carbon Fiber Composites Supply Chain Competitiveness Analysis." National Renewable Energy Lab. (NREL), Golden, CO (United States), May 1, 2016. http://www.osti.gov/scitech/biblio/1260138-global-carbon-fiber-composites-supply-chain-competitiveness-analysis.

8 Value chain analysis

8.1 Definition of value chains for targeted FCH applications

To define the value chains for FCH applications we make a conceptual distinction between the relatively narrow definitional scope of a supply chain, and the wider and deeper scope of the value chain definition. Essentially, in addition to the elements of the supply chain, the definitional scope of the value chain (as shown in Figure 49) includes:

- *Horizontal extensions*: post-production processes, such as distribution, after-sales (operations and maintenance support), end-of life / decommissioning (e.g. recovery, recycling, disposal);
- *Vertical extensions*: enablers, which can be sub-divided into:
  - Technology development processes: e.g. product/process technology development, production/manufacturing technology development and engineering;
  - Supporting business processes: e.g. logistics, finance, design, marketing and sales, customer services;
  - Other supporting processes: e.g. education and training, infrastructure development (e.g., fuelling stations in the case of transport applications) and policy making activities

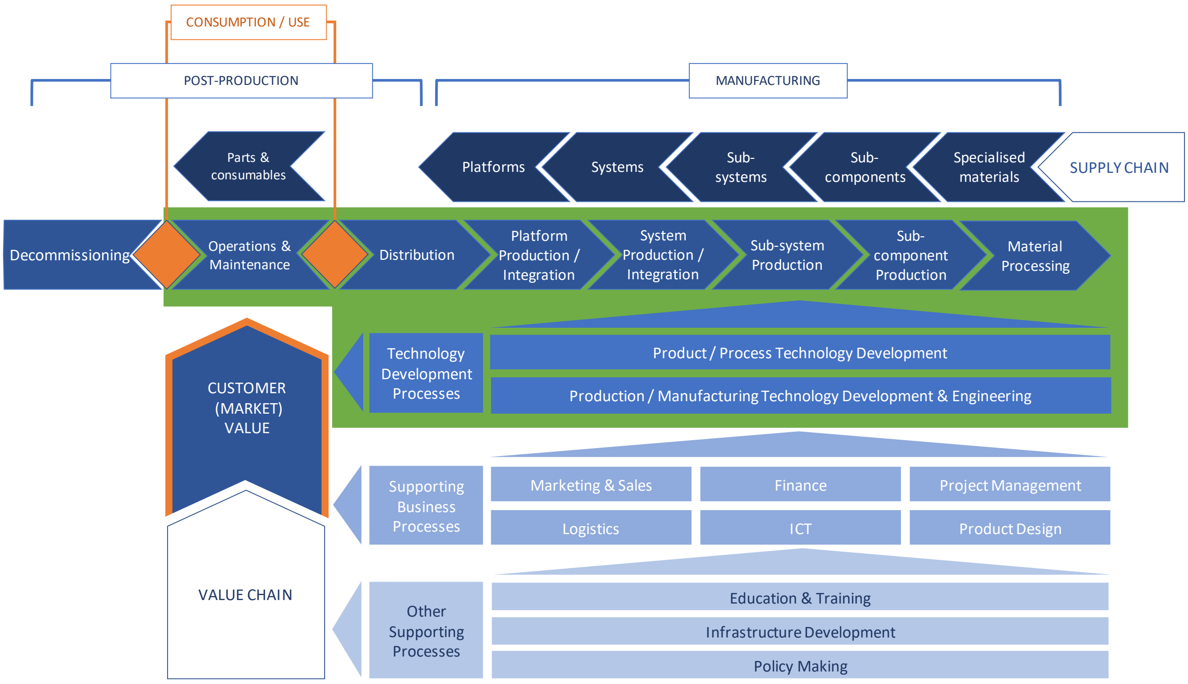


Figure 49: Stylised representation of a value chains

For the assessment of the potential for value creation, taking into account the availability of relevant data and information, we have employed both

- a narrow value chain definition, for which a quantitative assessment of the potential for value creation was undertaken, and
- a wide value chain definition, that includes additional elements for which qualitative assessments of value creation potential were made.

The narrow value chain definition encompasses value creation within the 'horizontal' supply chain (i.e., associated with, for example, materials processing, sub-component production, sub-system production, system production, platform production), together with distribution, and operations and maintenance activities. Also included in the narrow value chain definition are the 'vertical' elements associated with technology development processes; which covers both value creation potential arising from product-related and process-related technological development, as well as value creation potential arising through technological development related to production/manufacturing capabilities. The elements covered within the scope of the narrow value chain definition are shown within the green box in Figure 49.

In addition to the narrow value chain elements, the wide value chain definition encompasses the vertical element of 'supporting business processes' and 'other supporting processes'. It also covers 'horizontal' value creation arising from decommissioning.

For the purpose of assessing key competitiveness drivers, the EU's relative competitive position, and for the SWOT and gap analysis, our analysis was based on the wide value chain definition.

8.2 The shape of future supply chains

8.2.1 Supply chain definitions

To understand how FCH supply chains may evolve it is important firstly to establish a clear definition of a supply chain in the context of manufactured products. Although definitions vary slightly, **a supply chain is generally seen as the physical flow of raw materials and components from suppliers, through manufacturing, to finished goods delivered to customers**. Supply chain literature sometimes refers to webs rather than chains and to adjacent flows of data and money, but a physical flow definition is appropriate for this assessment. It is fully recognised that many other interactions occur.

Secondly it is important to define the perspective to be applied for examining future supply chains for manufactured goods. Manufactured products typically integrate a wide range of components and sub-assemblies, themselves made up of components and materials. Looking forwards along the chain, the customer of each supplier is the supplier of another, until the final consumer. For most fuel cell and hydrogen products the final consumer is a business, though not necessarily in the case of fuel cell cars and micro CHP. Given that fuels cells are not the end product and also that final distribution is not of primary interest for this study, the perspective applied here is of the product integrator[161] (also referred to as the assembler, product manufacturer, product builder or original equipment manufacturer (OEM) – according to industry custom). For integrators, fuel cells and hydrogen generally fall into the category of sourced components or specialised materials, at supply chain Tier 1 or 2, as illustrated in Figure 50.

[161] By contrast and to illustrate, an analysis of fast-moving consumer goods would need to look more closely at the distribution step.

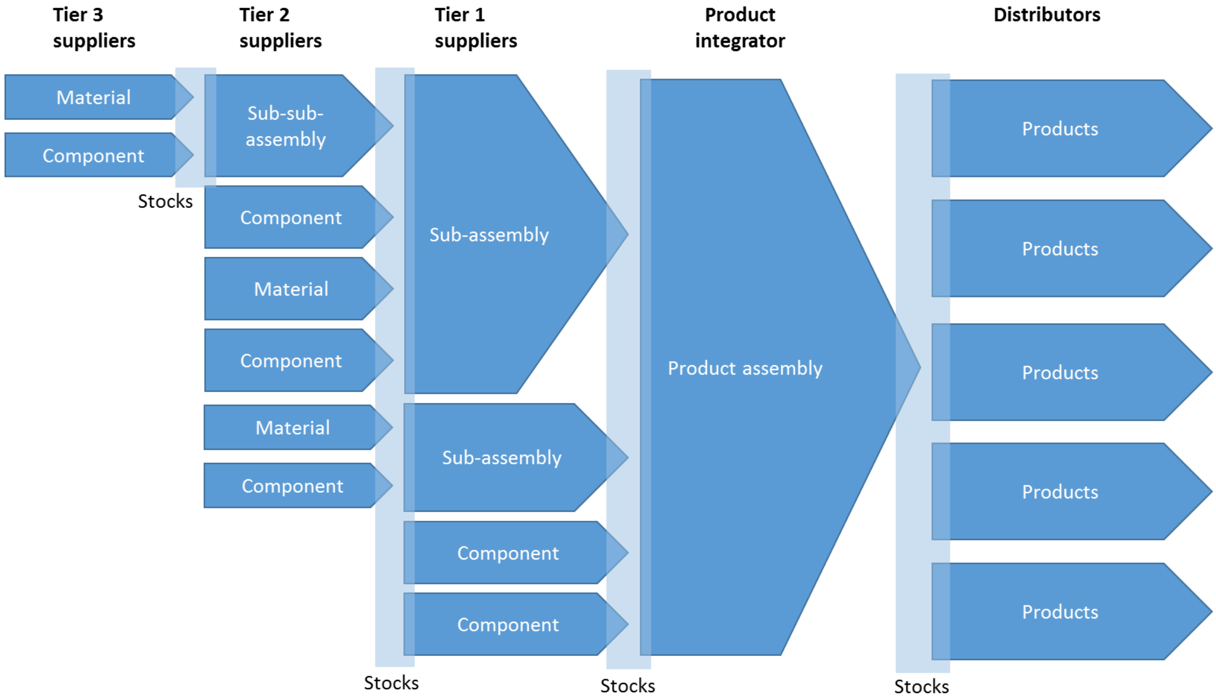


Figure 50: Illustrative supply chain for manufactured product showing physical flows

8.2.2 Manufactured product supply chain influences

In long-established industries powerful integrators developed over decades, and with them the capability to manufacture all but minor components. This vertical integration became commonplace in industries such as automotive and aerospace, but went into reverse from the 1980s as companies began to sell off non-core operations. Internal supply was replaced by procurement of components from tiered external suppliers (and services from outsourced providers), leaving integrators to focus on design, manufacture and brand-building. 'Supply chain management' emerged as a discipline, combining outward-facing planning, logistics, procurement and collaboration. Supply chain management continues to develop, supported by digital platforms providing easier collaboration and tighter connections than in the past.

Current FCH supply chains are immature. Several resemble the pre-supply chain management world, in which most components are made in-house (in small volumes). Sometimes FCH companies integrate their own final products to overcome lack of engagement by established manufacturers. This will change as markets grow, and many FCH supply chains will be reshaped. A central premise of the analysis is that the future supply chain shape for products featuring FCH will be determined by prevailing industrial logic and that FCH, though potentially different from incumbent technologies, will not fundamentally alter this logic. The term 'shape' is used here to describe several closely-related aspects of a supply chain from an integrator's perspective, in particular:

- The market needs and structure that determine what integrators require of suppliers
- The power and influence that integrators and suppliers can exert upon each other
- The customs and culture of integrator collaboration with suppliers
- The physical location of suppliers relative to integrators.

Shape is not solely a description of location and product flow therefore, though these are physical manifestations of the underpinning relationships and approach.

The four overlapping aspects of supply chain shape are broken down into five separate influence categories, as shown in Figure 51.

End consumer requirements	Consumer expectations of cost, delivery time, customisation and product life cycle set overall demands that flow along supply chain via integrators
Buying power of integrators	An industry with a few dominant integrators is more likely to control supplier prices and influence specifications than numerous smaller integrators
Component criticality, IP & value	An integrator of a sub-assembly or final product will seek to secure supply of high value or critical components by vertical integration or partnership with suppliers
Need for collaboration in supply chain	Innovation or co-development of components between supply chain partners is more readily achieved when language and distance do not create a barrier
Logistical and technical contraints	Bulky or hard to transport components need to be supplied close to point of assembly

Approach to market

Power & influence

Custom & culture

Location

Figure 51: Influences upon manufactured product supply chain shape[162]

The first of these aspects (end consumer requirements) is supported by analysis by H D Perez [163] which identifies different overall supply chain styles appropriate to customer needs, summarised as:

Efficiency-oriented supply chains:

a. *Lowest cost*. Commodity products made continuously in high volumes on a forecast-matching basis to ensure high utilisation. Examples: cement, chemicals
b. *Continuous flow*. Standard products made in high volumes on a make-to-stock basis so orders can be met without delay. High plant utilisation important. Examples: bread, household appliances
c. *Fast renewal*. Rapid product changes in response to market shifts, requiring short production runs against forecast. Standard materials, forecast accuracy and low stock levels keep costs down. Example: catalogue fashion goods.

Responsiveness-oriented supply chains:

d. *Agile*. Unique product specification per customer and unpredictable demand, satisfied by applying a make-to-order approach. Some excess capacity and small batch sizes enable fast response. Example: packaging, (some) military hardware
e. *Custom-configured*. Products configured from a set of components into one of several set variants according to customer order. To avoid delays and reduce costs, a continuous flow supply chain of main inputs is combined with agile assembly and delivery. Example: laptop computers, fast food restaurants
f. *Flexible*. Unpredictable and urgently-required products bespoke manufactured to order. Fast turnaround is assured by maintaining spare capacity and adaptable resources; cost is a lesser consideration. Example: oil platform replacement parts.

Despite this variety, only a small number of the above styles are likely to apply in mature supply chains featuring the FCH systems considered in this study. These are discussed in the following section, along with other influences on future supply chain development.

[162] Based upon work by E4tech and on H D Perez in www.supplychainquarterly.com/topics/Strategy/20130306-supply-chain-strategies-which-one-hits-the-mark/

[163] H D Perez in http://www.supplychainquarterly.com/topics/Strategy/20130306-supply-chain-strategies-which-one-hits-the-mark/

8.2.3 Implications for fuel cell and hydrogen supply chains

The influences discussed above will affect the supply chains for FCH products as they evolve from their current embryonic state towards (assumed) maturity and higher volumes. In this section the shape of example future supply chains is forecast based upon industrial logic, recognising that each chain has different characteristics. The combined implication of the influences for each example chain is summarised in Table 89.

Table 89: Potential supply chain shape for example future FCH-based products

Integrated product	Relevant FCH components	Descriptors of supply chain shape			
		Approach to market	**Power & influence**	**Custom & culture**	**Location**
Cars	Fuel cells, storage	Each OEM will offer range of FC powertrains, assembled into final product to match order	Strong OEMs will seek to own FC system design and assembly, and put cost pressure on component suppliers	Collaboration with e-chemistry suppliers may be needed, but more capable OEMs will build internal knowledge.	Regional if not local component supply to meet OEM demands
Buses	Fuel cells, storage	Bus builders will assemble FC 'engines' supplied as complete systems in low volumes, plus storage	Few bus builders able to exert strong price pressure, but will build close supply partnerships	FC development will be by FC system suppliers, also storage	FC and storage sourced globally, though some supplier regionalisation may occur to improve market access
Micro-CHP	Fuel cells	Continuous flow production to make standard products to stock	Large appliance makers may own stack supply, most will buy from close partners	Modular requirements may be used to diminish reliance upon a specific supplier	Regional or local stack supply preferred by large integrators
Larger CHP & primary power	Fuel cells	Low volume highly customised products	FC company may be final product integrator, or in partnership with a channel to market	FC company will require its suppliers to collaborate in product evolution	Product complexity and low volume make single assembly location per supplier most likely
Electrolysers	Electrolysers	Built to order products based on narrow range of product variants	Electrolyser company likely to be final product integrator	Electrolyser company will have key partners	Single assembly location per supplier likely

HRS	Compressors bulk storage	Built to order product configured from several options	The few HRS builders will work closely with suppliers of key components e.g. compressors	Co-development may not be needed, but local understanding of regulations helpful	Global supply possible, though hard for larger components (hydrogen storage)

Several overall observations emerge from this assessment:

- Most supply chains for finished products will evolve to a custom-configured style, with components and subassemblies supplied on a continuous flow basis and assembled and delivered on an agile basis (small CHP and very large power/CHP are possible exceptions).
- Powerful integrators control a large section of current ICE-based supply chains and are unwilling to allow value and control to leak from their domain. They will exert their power in a variety of ways (already evident in passenger car lithium-ion batteries), for example:
    - The most technically able vehicle integrators will develop in-house design and assembly of fuel cell systems, buying in components to a precise specification (which may be developed with expert support). This is equivalent to ICE design and manufacture. Hydrogen tanks could follow a similar route.
    - To prevent Tier 1 suppliers becoming too capable, critical components may be sourced on a 'make-to-print' basis rather than co-developed. This allows integrators to benefit from Tier 1 low cost manufacturing whilst controlling IP.
    - To avoid extended supply lines with high working capital value in transit and the risk of disruption, suppliers of critical components will co-locate with final assembly plants – in exchange for long term supply contracts.
    - Where an integrator of FCH systems has a complex product range requiring several FCH configurations, modular systems will be demanded of suppliers. This allows the integrator to easily reconfigure and allows them to compare several suppliers.
    - Partnering will be used by integrators to ensure ongoing access to future FCH technologies.
- Less powerful integrators will be in a weaker position to influence the specification, price and manufacturing location of FCH components. Examples include: buses, electrolysers, APUs, HRS and larger power/CHP – although exceptions may exist in all of these. Integrators will be keen to secure partnerships with relevant FCH suppliers in these supply chains.
- Integrators of APUs, electrolysers and large power/CHP sit close to the end of their supply chains, in some cases being the final product integrator. Their 'power' will depend upon market conditions, but supply chain management is as relevant to them as to other product integrators and they will need to secure supplies of critical inputs.
- The likely geographical location of FCH suppliers depends upon the power balance referred to above – those serving powerful integrators will be more likely to co-locate production with final assembly, though may keep R&D elsewhere. Supply volumes and ease of transportation also have a bearing upon location, but global supply from a single location could apply for integrators of some products such as APUs, electrolysers, HRS and large power/CHP. However, distributed supply may be chosen to satisfy market access considerations, especially where local content affects procurement; examples include buses and possibly HRS.

A graphical illustration (Figure 52) of the as-yet immature supply chain indicates one of the aspects under consideration[164]. In practice both of these options may exist simultaneously, for different sets of players.

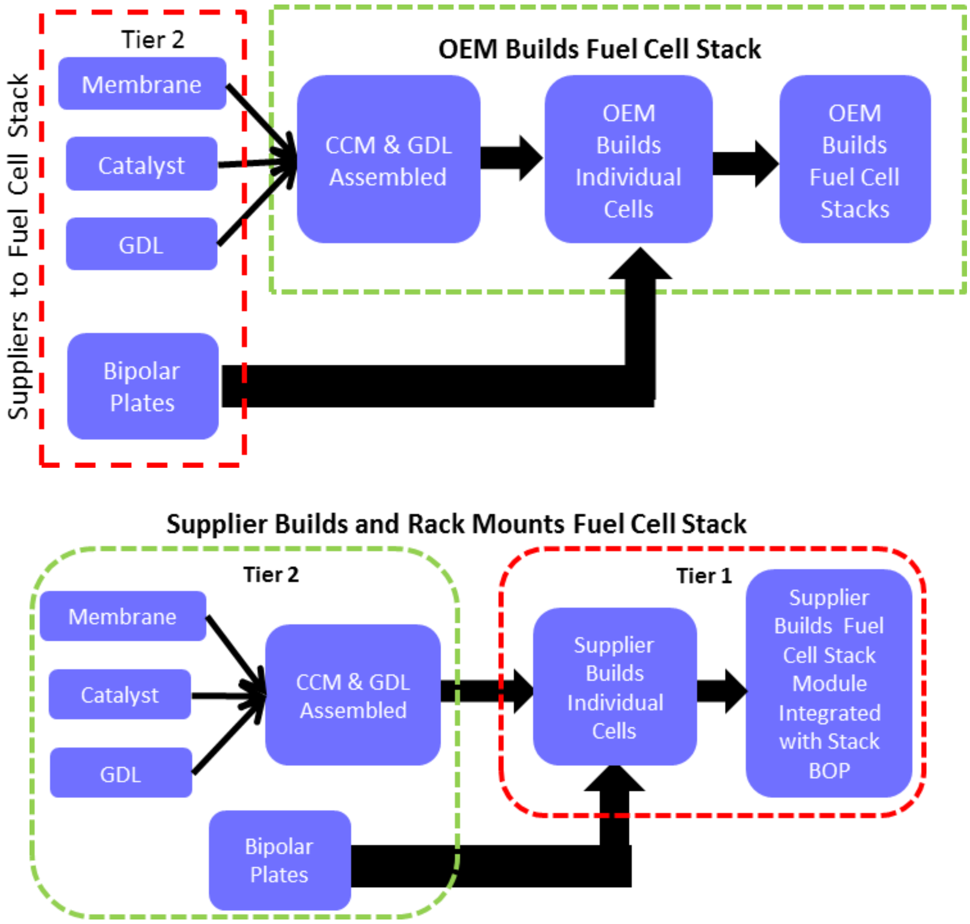


Figure 52: Two plausible options for future automotive FC supply chains[165]

In closing, it is important to note that this assessment of future supply chain shape assumes that FCH will reach maturity and will be adopted by integrators. In practice the ramp-up may not be smooth and intermediate supply chain states may apply. It will be important to identify the leading indicators that signal that a new stage is being reached and so the supply chain model should be adjusted.

8.3 Global and EU market scenarios to 2024 and 2030

8.3.1 Approach

Deployment scenarios have been developed for the global and EU markets for each application to 2024 and 2030. Three scenarios – for high, medium and low levels of deployment – in units and/or MW of capacity have been developed.

The scenarios reflect widely known scenarios and forecasts such as the IEA Energy Technology Perspectives, national existing FCH roadmaps, H2 mobility scenarios, scenarios from the Hydrogen Council and targets from national FCH funding programmes.

[164] After DJ Wheeler Technologies
[165] After DJ Wheeler Technologies

The specific approaches used to develop the scenarios depended on what data was available for a given application. Broadly, one or more of the four following approaches was used:

- **Existing application-specific forecast:** Where an application-specific forecast or scenario exists this was used or adapted. This was relevant for the most established applications such as FC passenger cars for instance.
- **Conventional application forecast plus an FCH penetration rate:** Where an application-specific forecast does not exist, a forecast of the equivalent conventional (non-FCH) application was used as the basis for the analysis. Different FCH penetration rates were used for the different scenarios. This approach was relevant for some of the vehicle applications, for instance HGVs.
- **Current conventional market plus growth and FCH penetration rate:** Where a forecast of the equivalent conventional application does not exist, a forecast was developed based on a current market size and assumed compound annual growth rate (CAGR). Different FCH penetration rates were then used to estimate the FCH application deployment.
- **Derived from other scenarios and forecasts:** For certain applications, a deployment estimate was derived from the scenarios for related applications. For instance for hydrogen refuelling stations, there will necessarily be a relationship between the size of the deployed FC vehicle fleets and the number of refuelling stations.

The deployment scenarios are then used to derive estimated annual sales. This data has been combined with the cost data to estimate global market turnovers by application and to inform the value chain and socio-economic impact analysis.

8.3.2 Deployment scenarios by application

The global and European deployment scenarios for each application are summarized in the tables below. Deployments are presented in both number of units and capacity as appropriate. To avoid double counting, no separate deployment scenarios for compressed hydrogen storage or fuel reformers are provided as these components are part of the systems in the other applications.

The deployment scenarios are not intended to be forecasts but rather to capture a range of outcomes that could reasonably be expected if the various applications begin to be deployed commercially. It is possible that commercial deployment of some applications may not start at all due to external factors such as a regulatory barrier in a key market or a policy driver that favours other solutions for that application.

Table 90: Global deployment scenarios in number of units

Application	Comments	Units	2024			2030		
			L	M	H	L	M	H
FCEV	Passenger cars and light commercial vehicles (LCV)	millions	0.33	0.90	1.8	1.6	5.5	10
FC Buses		thousands	16	24	35	61	120	190
HGV		thousands	3.0	3.8	10	20	37	80
FC Forklifts		thousands	48	67	93	85	140	230
Trains and light rail		units	87	190	490	420	1,200	2,400
Maritime and inland boats		units	16	38	110	75	240	520
HRS		thousands	0.76	1.9	3.9	3.5	11	20
Micro CHP	1-5 kW_e	millions	0.75	1.4	1.7	2.3	4.8	7.0
Commercial CHP	5-100 kW_e	thousands	4.7	7.3	26	31	72	200
Large CHP	> 100 kW_e	thousands	7.3	14	27	17	45	97
Back-up power and gensets		thousands	42	60	75	85	150	230
Electrolysers	Not applicable as stack sizes vary significantly							

Table 91: Global capacity deployment scenarios in watts

Application	Comments	Units	2024			2030		
			L	M	H	L	M	H
FCEV	Passenger cars and light commercial vehicles (LCV)	GW	34	84	170	170	560	1,000
FC Buses		GW	2.0	3.0	4.5	8.0	16	26
HGV		GW	0.60	0.75	2.1	3.9	7.5	16
FC Forklifts		MW	240	340	470	420	710	1,100
Trains and light rail		MW	26	58	150	130	360	710
Maritime and inland boats		MW	9.4	23	65	45	140	310
HRS	Not applicable							
Micro CHP	1-5 kW	GW	0.8	1.5	1.8	3.0	5.7	10
Commercial CHP	5-100 kW	GW	0.5	0.7	2.6	3.1	7.2	20
Large CHP	> 100 kW	GW	7.3	14	27	17	45	97
Back-up power and gensets		MW	70	140	150	190	400	570
Electrolysers		GW	1.6	3.2	4.5	5.6	12	21

Table 92: European deployment scenarios in number of units

Application	Comments	Units	2024			2030		
			L	M	H	L	M	H
FCEV	Passenger cars and light commercial vehicles (LCV)	millions	0.060	0.20	0.48	0.3	1.2	2.6
FC Buses		thousands	1.0	1.7	3.0	3.6	8.4	16
HGV		thousands	0.44	0.66	2.20	2.90	6.5	17
FC Forklifts		thousands	0.96	2.0	4.7	1.7	4.3	11
Trains and light rail		units	23	61	180	110	390	870
Maritime and inland boats		units	2	4	11	8	24	52
HRS		units	130	400	990	600	2,300	5,000
Micro CHP	1-5 kW_e	millions	0.05	0.12	0.18	0.16	0.43	0.77
Commercial CHP	5-100 kW_e	thousands	0.27	0.75	3.5	1.8	7.5	27
Large CHP	> 100 kW_e	thousands	0.07	0.65	2.2	0.29	4.0	10
Back-up power and gensets		thousands	1.3	3.0	5.2	2.5	7.6	16
Electrolysers	Not applicable as stack sizes vary significantly							

Table 93: European capacity deployment scenarios in watts

Application	Comments	Units	2024			2030		
			L	M	H	L	M	H
FCEV	Passenger cars and light commercial vehicles (LCV)	GW	6.2	19	45	31	120	270
FC Buses		GW	0.12	0.21	0.38	0.47	1.1	2.2
HGV		GW	0.09	0.13	0.43	0.57	1.3	3.3
FC Forklifts		MW	4.8	6.7	9.3	8.5	14	23
Trains and light rail		MW	7.0	18	54	34	120	260
Maritime and inland boats		MW	1.2	2.4	6.6	4.8	14	31
HRS	Not applicable							
Micro CHP	1-5 kW	GW	0.06	0.13	0.20	0.21	0.51	1.0
Commercial CHP	5-100 kW	GW	0.03	0.08	0.35	0.18	0.75	2.7
Large CHP	> 100 kW	GW	0.070	0.65	2.2	0.29	4.0	10
Back-up power and gensets		MW	2.1	6.9	10	5.8	20	40
Electrolysers		GW	0.52	0.81	0.91	1.8	3.0	4.3

8.3.3 Turnover of the global market

Based on the global deployment scenarios given above and the cost breakdown data presented in Section 4.2, an estimate of the range of global turnover associated with each application is given in Table 94 below. Note that for the transport applications the turnover estimate is based on the cost of just the fuel cell and hydrogen components – i.e., the cost of the rest of the vehicle is not included.

More detailed assessments of the economic value of selected applications in Europe is given in the value chain analysis in Sections 8.4 and 8.6.

Table 94: Global turnover estimate

Application	Comments	2024 € millions	2030 € millions
FCEV	Passenger cars and light commercial vehicles (LCV)	1,000-5,100	1,900-9,800
FC Buses		240-520	390-1,400
HGV		66-220	170-580
FC Forklifts		19-52	19-64
Trains and light rail		5-29	11-50
Maritime and inland boats		4-24	7-37
HRS		1,300-6,400	3,500-18,000
Micro CHP	1-5 kW	390-1,300	1,100-3,600
Commercial CHP	5-100 kW	290-1,700	910-5,400
Large CHP	> 100 kW	1,500-9,100	2,500-16,000
Back-up power and gensets		36-82	37-140
Electrolysers		230-740	450-2,000
Total		5,200-25,000	11,000-57,000

8.4 Value analysis

8.4.1 Estimation of value-added creation potential within FCH supply chains

This sub-section presents an assessment of the value creation potential of supply chains for FCH applications. The assessment uses estimates of the cost breakdown for FCH systems (provided in Section 4.2), consistent with the global and EU market deployment scenarios – for high, medium and low levels of deployment – which are translated into annual production volumes for 2024 and 2030.

The assessment of the value creation potential of production activities within the supply chain uses an economic value-added approach, where (gross) value-added equates to the sum of compensation of labour, return on capital (i.e. annualised capital expenditures, capex) and a margin (i.e. gross profits) as shown in Figure 53.

In practice value-added is the difference between the price of a manufactured part and the price of the materials and components used to manufacture it, and is typically a small fraction of the overall price of the part. Equivalently, value-added is the difference between the value of production outputs (i.e. sales revenue or turnover) and the cost of intermediate production inputs, including overhead costs.

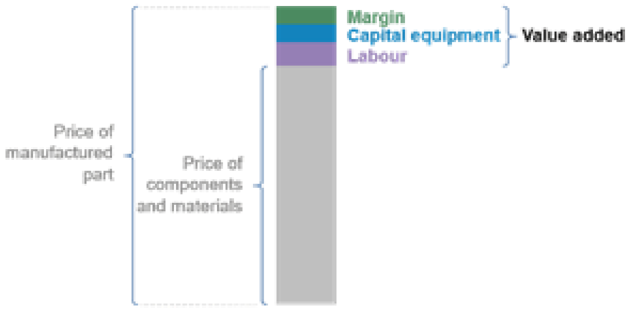


Figure 53: Definition of value-added

The estimates provided in this sub-section are indicative only. Their purpose is to support the assessment of the relative value creation potential across selected FCH applications at the FC system level, and from the production of different components and sub-systems, including assembly and integration activities. The estimates are based on assumed 'typical' production structures and cost estimates, and assumptions on cost development occurring over time and for different production scales. The estimates are used to categorise the value creation potential of production activities within the supply chain and should not be interpreted as estimates of actual future value-added potential. All monetary values are expressed in current (2017) prices.

8.4.1.1 Approach to the calculation of supply chain cost estimates

For each critical component, a learning rate curve was developed. Where detailed, bottoms-up cost studies were available, the reported data were fit to a learning rate for each critical component. Figure 54 shows an illustrative example of a curve fit to several data sources for a PEM membrane electrode assembly. Learning rate cost curves for individual sub-components—catalyst, membrane, and gas diffusion layer, for example—were similarly developed. It was possible to directly fit available cost data for the majority of the applications and critical components; however, it was necessary to assume a cost correlation for applications for which only survey-based system costs were available.

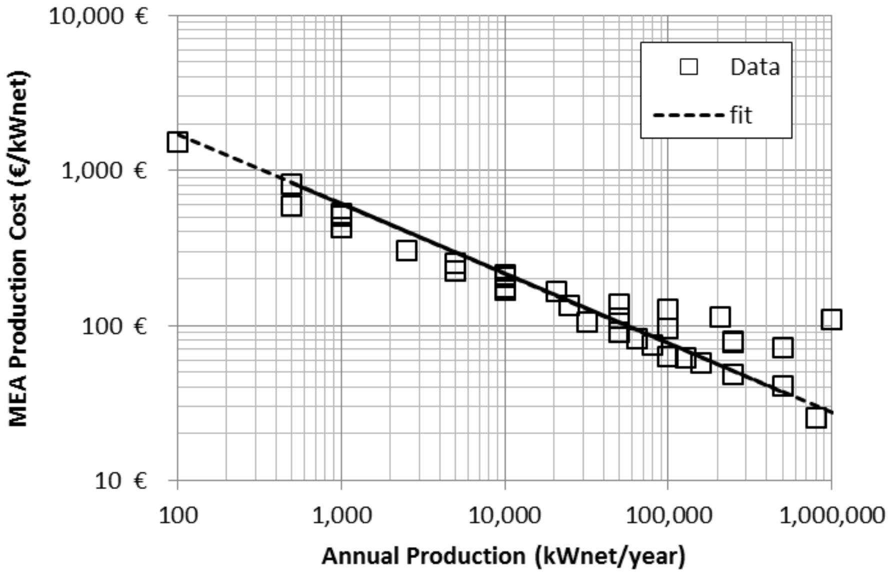


Figure 54: Illustrative example of fitting cost analysis data from multiple sources

The cost curves were expressed in terms of unit annual production (e.g. kW/year, kgH_2/year, etc.), which allowed deployment specific component costs across multiple unit sizes to be predicted. The leading producer annual production is set at 60% of annual deployments, which is used in the value-added calculations. Due to their modular nature, annual production of fuel cell stacks for bus, HGV, and train applications are assumed to come from a single supplier. This assumption effectively decreases the cost by sharing manufacture for multiple applications. By contrast, deployments of some applications such as electrolysers and commercial CHP systems represent aggregate deployments for all chemistries, thus it was necessary to disaggregate them.

Material, labour, and capex splits for each component were derived from the cost studies based on their contributions at full production plant utilization to prevent spurious high capex contributions due to oversized manufacturing equipment.

The distinction between cost and price depends on the perspective within the value chain. Cost, throughout this analysis refers to a supplier's cost, whereas price refers to the estimated 'factory-gate' price (or cost) for the end-user. Following on the example of an MEA, the sub-component cost breakdowns for catalyst, GDL, and membrane to the MEA manufacturer include a mark-up for each respective supplier. Similarly, the MEA material cost to the fuel cell integrator includes a mark-up the MEA manufacturer applies. Mark-up rate assumptions are described below.

8.4.1.2 Approach to the calculation of supply chain value-added

The estimation of (gross) value-added potential is composed of three components:

- **Labour:** taken directly from the calculation of cost estimates;
- **Capital:** taken directly from the calculation of cost estimates;
- **Margin (or profit):** The estimation of the margin is based on two elements:
    - **Standard ('normal') margin.** The standard margin (profit rate) is set at 5% of the total cost of production inputs (labour + capex + materials and other intermediate production inputs), excluding overhead costs. The standard profit rate is applied to all production steps (i.e. production of components and sub-systems, and integration and assembly activities).

- **Excess ('supra-normal') margin.** The excess margin (profit rate) is based on an evaluation of the supply characteristics of each production step. It is intended to 'proxy' the additional margin that may arise as a result of some form of market dominance of firms active within the production step resulting from market (supply) entry barriers. Such barriers may include *inter alia* intellectual property (e.g. patents, proprietary technology, know-how, etc.), investment costs (e.g. costs of R&D or production capital), presence of scale economies for incumbent suppliers, etc. Three values for the excess margin are used in the value-added estimations: zero (0%, only standard margin applies), medium (5%), high (10%). In contrast to the standard margin, it is assumed that excess margins are not charged on the cost of materials and other intermediate production inputs but only on labour and capital costs (capex).

It should be noted that if a standard margin is assumed for all production inputs within a system, and corresponding integration and assembly activities, the estimated market revenues correspond directly with the baseline revenue estimates for the global and EU market deployment scenarios. Where an excess margin is applied to one or more elements of the supply chain, it will result in higher revenue estimates than those of the baseline market deployment scenarios.

Table 95: Assumed excess margin by application and production step – PEM fuel cells

Activity/Component	PEMFC				
	FCEV	Buses, HGVs, Trains	Micro - CHP	CHP	Electrolyser
System integration	High	High	High	High	High
Tank	High	High	N/A	N/A	N/A
Balance of plant	Medium	Medium	Medium	High	Medium
Stack integration	High	High	Medium	Medium	High
Balance of stack	Medium	Medium	Medium	Medium	Medium
Bipolar plates	Medium	Medium	High	High	High
MEA	High	High	Medium	Medium	Medium
Membrane	High	High	High	High	High
Catalyst	Zero	Zero	High	High	High
GDL/Porous layer	High	High	High	High	Medium

Table 96: Assumed excess margin by application and production step – Solid oxide fuel cells

Activity/Component	SOFC		
	Micro-CHP	CHP	Electrolyser
System integration	High	High	High
Balance of plant	Medium	Medium	Medium
Stack integration	High	High	High
Balance of stack	Medium	Medium	Medium
Interconnectors	Zero	Zero	Medium
Porous layers	Zero	Zero	Medium
Seals	Zero	Zero	Medium
Cells	Medium	Medium	High

Table 97: Assumed excess margin by production step – Hydrogen refuelling stations

Activity/Component	Hydrogen refuelling station
Station integration	Medium
Balance of station	Medium
Compression	Medium
Dispensers	High

Note regarding system cost breakdowns

The cost breakdowns used in the value-added analysis below and reported earlier in Section 4.2 are essentially derived from the same reference data. However, to enable the value-added analysis, projections of margin, capital equipment and labour contributions to individual components costs needed to be developed. Each of these contribution projections needed to be matched to the annual production volumes from the deployment scenarios. This required cost curves for each contribution. The introduction of these additional cost curves and the adjustments to the margin discussed above mean that the system costs reported in Sections 4.2 and 8.4 are not identical. Any differences between the two are, however, well within the overall uncertainty of the analysis.

8.4.2 Overview of supply chain value-added estimates

Value is added at each stage of the manufacturing process. For later manufacturing stages, value-added from earlier stages becomes part of the price of materials (Figure 55). By tracking the value added for key components as well as for the system, the study is able to provide insight into which parts of the supply chain have the potential to create the biggest economic benefits.

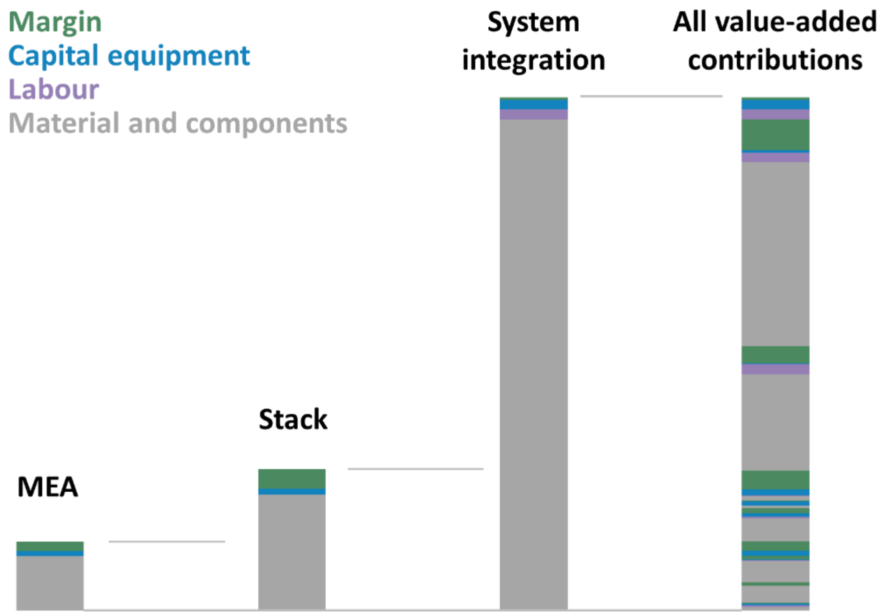


Figure 55: Build-up of value-added through the supply chain illustrating that value-added is typically a small fraction of turnover

The different elements of value-added yield economic benefits in different ways:

Labour

- Value is captured as local employment
- Manufacturing plants located in the EU yield EU value
- Home country of business entity is not critical

Capital

- Value is captured by suppliers of capital equipment
- Requires EU capital equipment suppliers to yield EU value

Margin

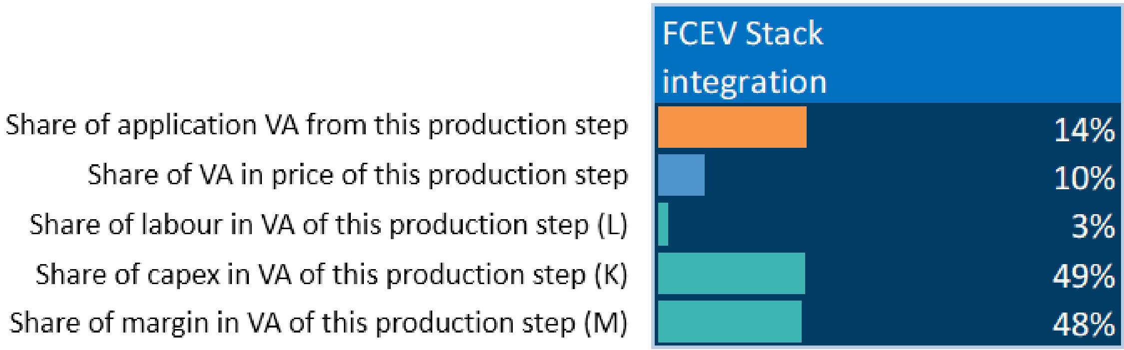
- Captured as revenues of business entity
- Requires EU business entity to yield EU value

The sections below present the estimated breakdown of value-added generated in the supply chain of fuel cell systems for each of the selected applications. The box below gives a short description of the interpretation of the value-added indicators shown in the figures for each application.

Interpretation of value-added decomposition figures

For each element (stage) in the supply chain:

- **Row 1** (orange bar) shows the share of the production stage in total value-added created in the FCH system supply chain. The higher the value shown for a production stage, the greater is its share of total value-added generated within the supply chain for the FCH system.
- **Row 2** (blue bar) shows the intensity of value-added creation of the production stage, measured as the ratio of value-added (labour, capital consumption, and margin) to the sum of value-added plus overheads and the cost of added materials, where added materials includes the costs of components and sub-systems for which costs are attributed elsewhere in the overall supply chain calculations. A high value indicates that this production step generates a lot of value-added compared to the costs of performing that step.
- **Rows 3 to 5** (turquoise bars) show the composition of value-added of the production stage in terms of the share of its labour (L), capital cost (K) and margin (M) components.



8.4.2.1 Estimated value creation potential for FC systems for passenger cars and light commercial vehicles

Figure 56 and Figure 57 show the estimates of the breakdown of value-added for FC systems for passenger cars and light commercial vehicles, under the low and high market scenarios for 2030; corresponding to annual production volumes of 300 thousand and 1.8 million vehicles, respectively. A comparison of the breakdown of value-added creation for all three deployment scenarios for the years 2024 and 2030 is given in Table 98.

The pattern of value-added estimates indicates that at low levels of production, membrane electrode assembly (MEA) activities capture the greatest share of total value-added generated in the supply chain of fuel cell systems for cars and light trucks – 27% of value-added in the low scenario for 2030 – but their share declines substantially as production levels are scaled-up; the share of MEA falls to 8 percent by 2030 under the high deployment scenario. Conversely, the share of value-added captured by system integration increases at higher production levels, as is also the case for hydrogen tanks. These findings reflect differences in the underlying assumptions for opportunities for overall cost (output price) reductions at higher volumes of production, which are assumed greater for MEAs than for system integration and tanks. In terms of value capture across downstream and upstream manufacturing, the estimations clearly show that more value is captured downstream (at the system and subsystem level). This holds for both low and high market deployment scenarios. Notably, a large part of overall value creation potential is embedded in integration and assembly activities.

The highest intensity of value-added creation, at around 60 percent, is in the production of balance of stack items, which covers components such as seals and compression hardware. However, as is also the case for the balance of plant at the system integration stage, this reflects an average estimate across a variety of components for which separate cost estimates have not been made. Gas diffusion layer (GDL) production has the second highest share of value-added in both high and low scenarios, at slightly less than 50 percent. However, despite this high share, the value-added captured at the GDL stage remains low at only 5 percent of total value-added generated in the FCEV supply chain in the low scenario, which decreases as production levels increase.

In terms of the breakdown of value-added by ‘production factor’ category, under all deployment scenarios the highest overall share is attributed to the annualised cost of capital (capex), which is estimated to account for about half of value-added generated in the low scenario for 2024 and a third of value-added in the high scenario for 2030. Both the share of labour costs and the share of margins in total value-added are shown to rise with increases in the volume of production, with the share of labour costs increasing slightly more rapidly than the share of margins. At the level of individual components and integration/assembly activities, the share of labour costs in total value-added is estimated to be relatively high for balance of plant (for system integration), tanks, gas diffusion layer (GDL), and system integration. The share of capital costs in value-added is highest for balance of stack, membrane electrode assembly, and bipolar plates.

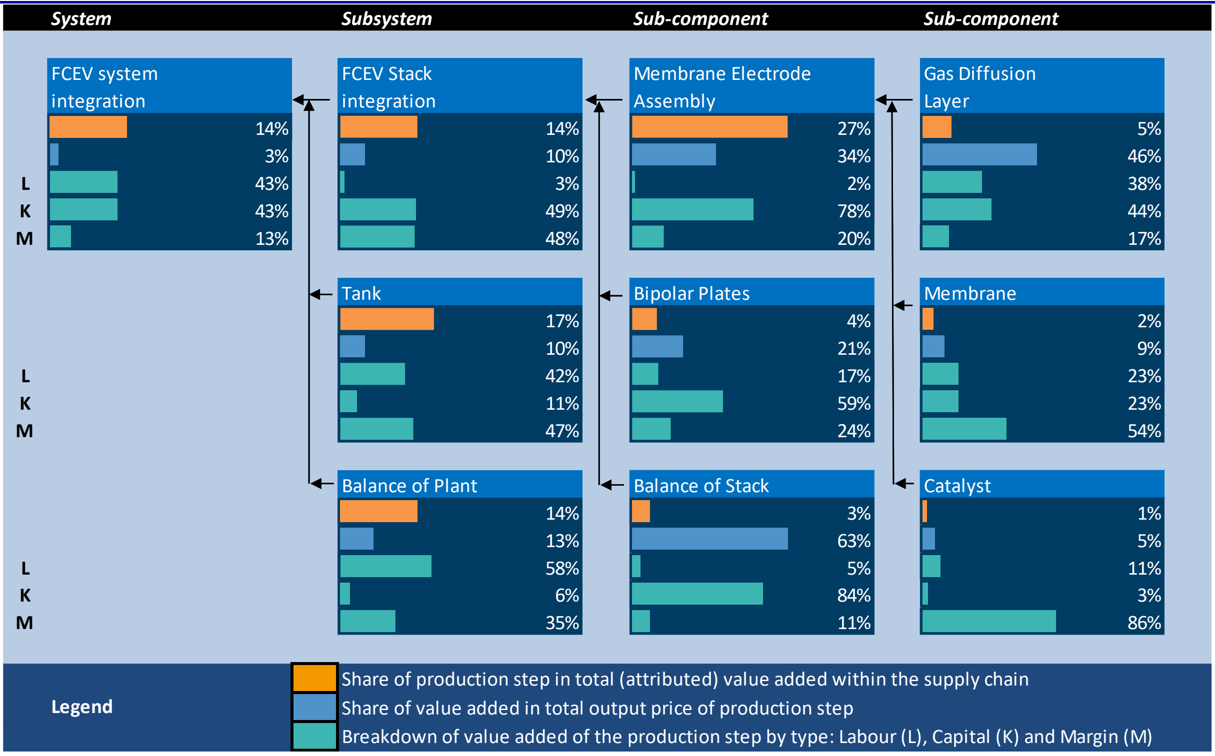


Figure 56: Value-added decomposition for FC system for cars and light commercial vehicles, low market deployment scenario, 2030

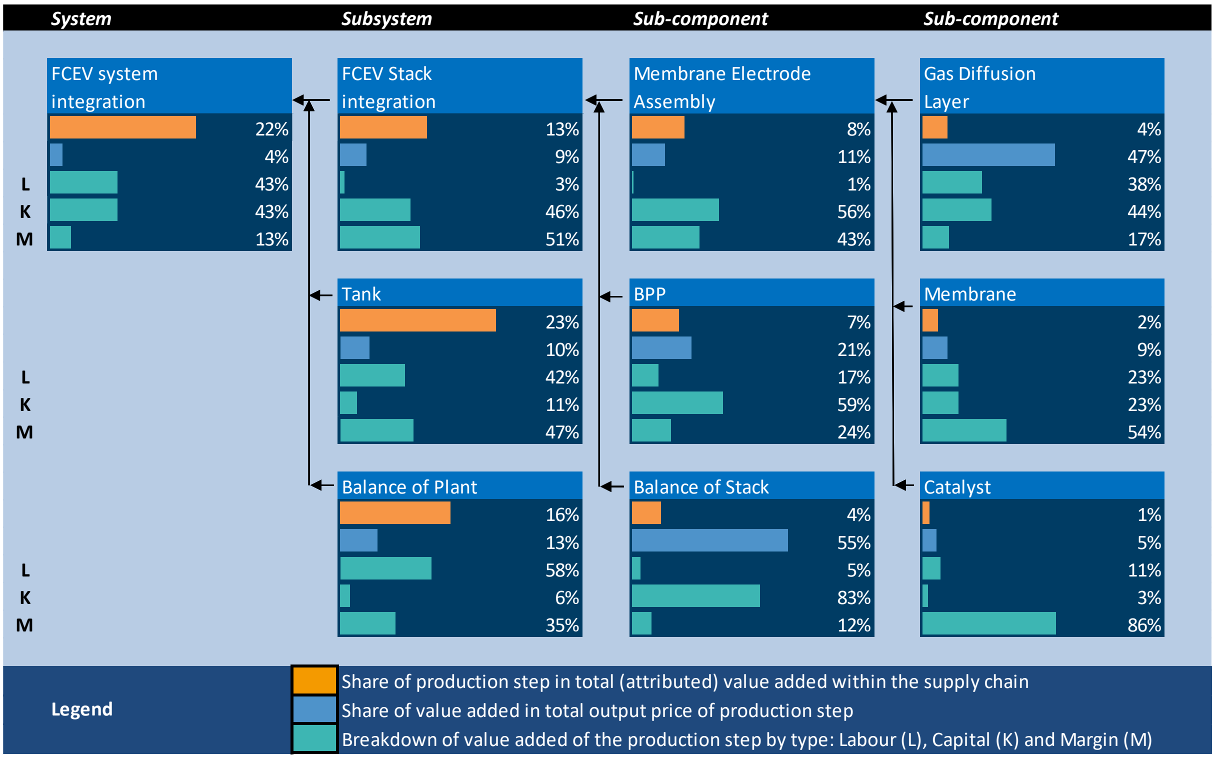


Figure 57: Value-added decomposition for FC system for cars and light commercial vehicles, high market deployment scenario, 2030

Table 98: Value-added decomposition for FC system for cars and light commercial vehicles by market deployment scenario, 2024 and 2030

Year	2024			2030		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Thousand units)	95	352	645	304	1,062	1,796
Annual production rate of leading manufacturer (Thousand units)	57	211	387	182	637	1,077
System cost (Output price)	€ 10,800	€ 7,800	€ 6,800	€ 8,100	€ 6,100	€ 5,400
Total VA within system	€ 2,900	€ 1,800	€ 1,500	€ 1,900	€ 1,300	€ 1,100
Application VA as a share of total costs (VA / output price)	27%	23%	22%	23%	21%	20%
Rate of VA (VA / material & overhead costs)	37%	30%	28%	31%	27%	26%
Breakdown of VA by component or activity						
Total VA in system (excl. MEA and Stack)	**35%**	**45%**	**51%**	**44%**	**55%**	**61%**
FCEV system integration	10%	14%	17%	14%	19%	22%
Tank	13%	17%	19%	17%	21%	23%
Balance of Plant	12%	14%	15%	14%	16%	16%
Total VA in stack (excl. MEA)	**19%**	**21%**	**21%**	**21%**	**23%**	**24%**
FCEV Stack integration	14%	13%	13%	14%	13%	13%
Bipolar Plate	3%	5%	5%	4%	6%	7%
Balance of Stack	2%	3%	3%	3%	4%	4%
Total VA in MEA	**46%**	**34%**	**28%**	**35%**	**22%**	**15%**
ME Assembly	38%	26%	20%	27%	14%	8%
Gas Diffusion Layer	6%	5%	5%	5%	4%	4%
Membrane	2%	2%	2%	2%	2%	2%
Catalyst	0%	1%	1%	1%	1%	1%
Breakdown of total VA by cost category						
Labour cost	21%	26%	28%	25%	30%	33%
Capex cost	50%	43%	40%	45%	37%	33%
Margin	28%	31%	32%	30%	33%	34%
Total	100%	100%	100%	100%	100%	100%
Notes: numbers may not add up due to rounding of data						

8.4.2.2 Estimated value creation potential for FC systems for buses

The estimates of the breakdown of value-added for FC systems for buses under the low and high market scenarios for 2030 are presented in Figure 58 and Figure 59. Under the low scenario, the annual global production volume corresponds to 10 thousand vehicles, while 40 thousand buses would be produced under a high scenario. The breakdown of value-added creation for all three scenarios, for both 2024 and 2030, can be found in Table 99.

As with FCEVs, at low levels of production MEA activities capture the greatest share of total value-added generated in the supply chain of fuel cell systems for buses (37% of value-added generated in the low scenario for 2030), followed by hydrogen tanks (26% of value-added). At higher production volumes, the position of these two segments is reversed, with MEA activities capturing 26 percent of value-added and tanks capturing 33 percent in the high scenario for 2030. Given the relatively modest production levels, even under the high scenario, opportunities for reduction in costs arising from increased volumes of production of MEAs and associated sub-components are less pronounced than for FCEVs. Thus, the estimates show a more modest shift of value capture from upstream to downstream manufacturing with higher production volumes. Overall, system integration activities are estimated to represent only a modest part of overall value-added generated in the supply chain of fuel cell systems for buses, achieving only 6 percent in the high scenario for 2030.

In terms of the intensity of value-added creation of different production segments, this is highest for the balance of stack (70% under the low scenario and 67% under the high scenario for 2030), followed by MEA activities (50% and 41%) and the GDL (46% in both scenarios), although GDL accounts for only around 5 percent of total value-added generated in the supply chain of fuel cell systems for buses.

As with systems for FCEVs, under all deployment scenarios the annualised cost of capital (capex) represents the largest share of value-added when broken down by ‘production factor’. Capex is estimated to account for about half of value-added generated, with its share ranging from 54 percent in the low scenario for 2024 to 44 percent of value-added in the high scenario for 2030. Both the share of labour costs and the share of margins in total value-added are shown to rise modestly with increases in the volume of production. At the level of individual components and integration/assembly activities, the share of labour costs in total value-added is estimated to be relatively high for balance of plant (for system integration) and system integration, together with tanks and the gas diffusion layer (GDL). The share of capital costs in value-added is highest for membrane electrode assembly, bipolar plates and stack integration.

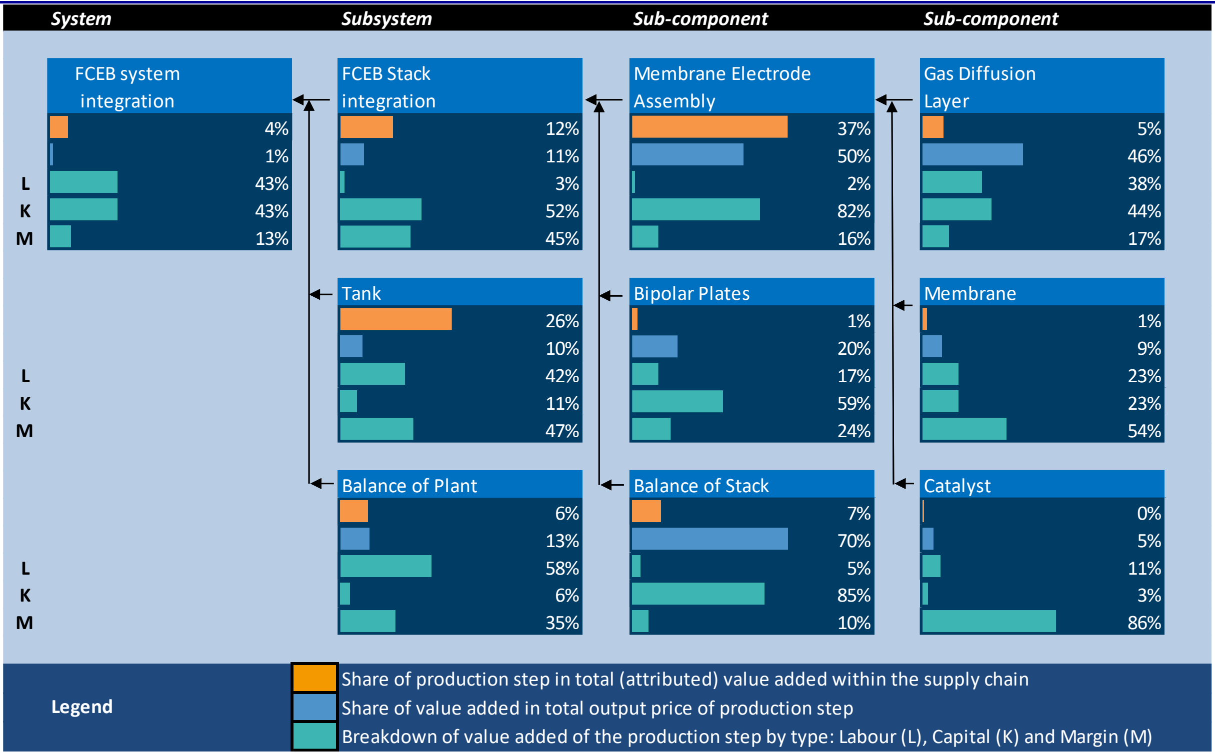


Figure 58: Value-added decomposition for FC system for buses, low market deployment scenario, 2030

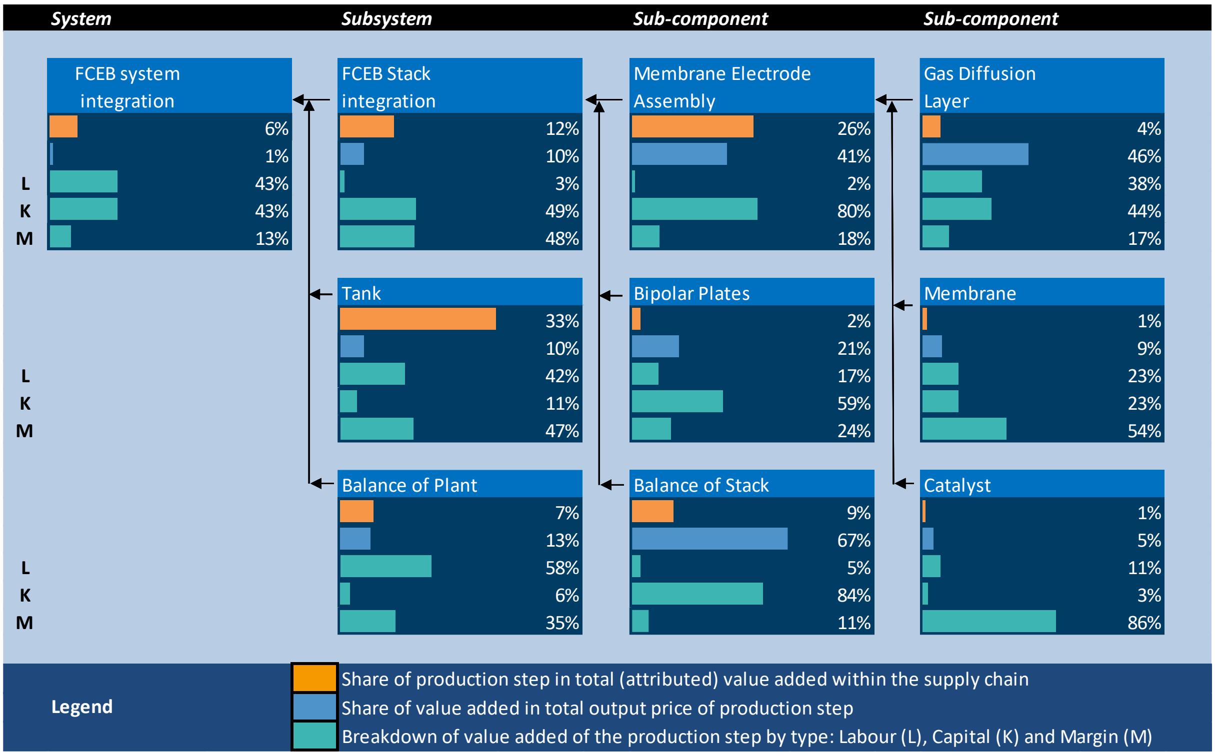


Figure 59: Value-added decomposition for FC system for buses, high market deployment scenario, 2030

Table 99: Value-added decomposition for FC system for buses by market deployment scenario, 2024 and 2030

Year	**2024**			**2030**		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Thousand units)	4	8	10	10	23	40
Annual production rate of leading manufacturer (MW)	500	800	1,400	1,400	3,000	5,400
System cost (Output price)	€ 59,400	€ 52,300	€ 46,600	€ 46,900	€ 39,500	€ 34,900
Total VA within system	€ 15,400	€ 12,800	€ 10,600	€ 10,900	€ 8,400	€ 6,900
Application VA as a share of total costs (VA / output price)	26%	24%	23%	23%	21%	20%
Rate of VA (VA / material & overhead costs)	35%	32%	29%	30%	27%	25%
Breakdown of VA by component or activity						
Total VA in system (excl. MEA and Stack)	**31%**	**34%**	**38%**	**37%**	**42%**	**46%**
FCEB system integration	3%	4%	4%	4%	5%	6%
Tank	22%	24%	27%	26%	30%	33%
Balance of Plant	6%	6%	6%	6%	7%	7%
Total VA in stack (excl. MEA)	**19%**	**19%**	**20%**	**20%**	**21%**	**22%**
FCEB Stack integration	13%	12%	12%	12%	12%	12%
Bipolar Plate	1%	1%	1%	1%	2%	2%
Balance of Stack	5%	6%	7%	7%	8%	9%
Total VA in MEA	**50%**	**47%**	**43%**	**43%**	**37%**	**31%**
ME Assembly	44%	40%	36%	37%	31%	26%
Gas Diffusion Layer	6%	5%	5%	5%	4%	4%
Membrane	1%	1%	1%	1%	1%	1%
Catalyst	0%	0%	0%	0%	0%	1%
Breakdown of total VA by cost category						
Labour cost	18%	19%	20%	20%	22%	24%
Capex cost	54%	52%	50%	50%	47%	44%
Margin	28%	29%	30%	29%	31%	32%
Total	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Notes: numbers may not add up due to rounding of data						

8.4.2.3 Estimated value creation potential for FC systems for HGVs

The estimates of the breakdown of value-added for FC system for HGVs under the low and high market scenarios for 2030 are presented in Figure 60 and Figure 61. Under the low scenario, the annual global production volume corresponds to 4 thousand vehicles, while 17 thousand fuel cell HGVs are produced under a high scenario. The breakdown of value-added creation for all three scenarios, for both 2024 and 2030, can be found in Table 100.

> ***Note:*** *As the underlying cost models assume that fuel cell production for buses, HGVs and trains is based on the same production technology and fuel cell component configuration (catalyst, GDL, MEA, bipolar plated, balance of stack and balance of plant), with overall production learning cost reduction factors reflecting a cumulative effect across these application types, the pattern of GVA creation and intensity is similar across the three application types. Differences arise because of the different size of stacks and tanks used for each application.*

MEA activities are estimated to generate the largest share of total value-added in the supply chain of fuel cell systems for HGVs. Although this share declines with increased production volumes – from 40% in the low scenario for 2030 to 29% in the high scenario HGVs – it remains greater than the value-added generated by production of tanks, which reaches 26 percent under the high scenario for 2030. Stack integration, which is steady at around 13 percent of total value-added, has the third largest share in the supply chain of FC system for HGVs.

Reflecting the common cost model used, the intensity of value-added creation in the supply chain for fuel cell systems for HGVs is essentially the same as for buses. Value-added intensity is highest for the balance of stack, followed by MEA activities and the GDL. Also, the breakdown of value-added generation by 'production factor' has the same pattern as for buses, with differences arising due to the relative share of the fuel cell stack, tank and balance of plant in the overall cost of the fuel cell system for different applications. Under all deployment scenarios the annualised cost of capital (capex) represents the largest share of value-added when broken down by 'production factor', ranging from 57 percent in the low scenario for 2024 to 48 percent of value-added in the high scenario for 2030. Both the share of labour costs and the share of margins in total value-added are shown to rise modestly with increases in the volume of production.

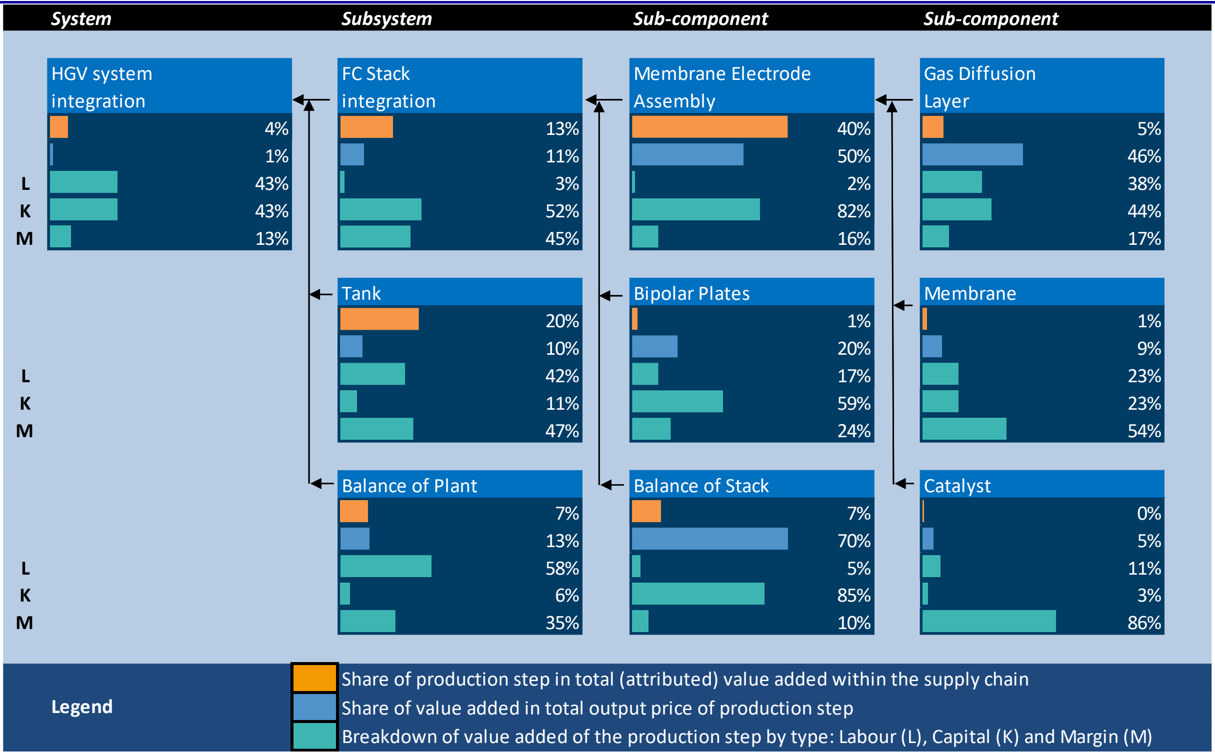


Figure 60: Value-added decomposition for FC system for HGVs, low market deployment scenario, 2030

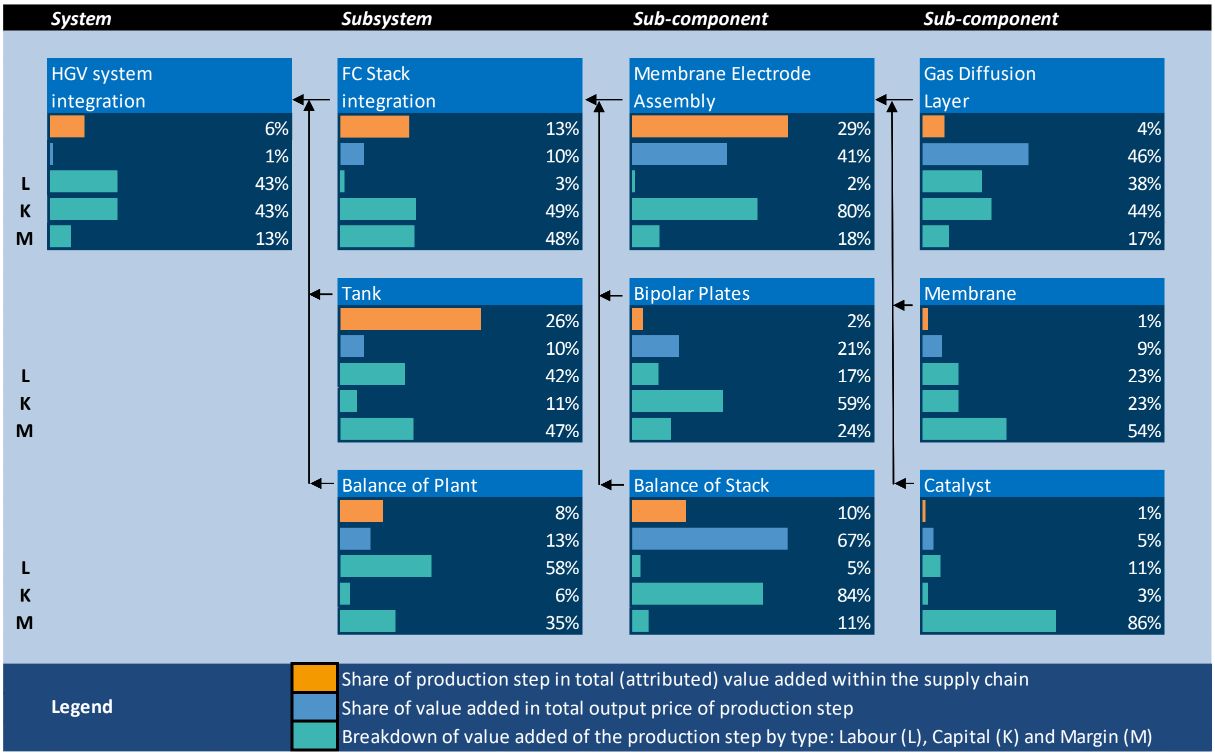


Figure 61: Value-added decomposition for FC system for HGVs, high market deployment scenario, 2030

Table 100: Value-added decomposition for FC system for HGVs by market deployment scenario, 2024 and 2030

Year	**2024**			**2030**		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Thousand units)	1	2	4	4	9	17
Annual production rate of leading manufacturer (MW)	500	800	1,400	1,400	3,000	5,400
System cost (Output price)	€ 70,600	€ 61,600	€ 54,400	€ 54,700	€ 45,600	€ 40,000
Total VA within system	€ 20,600	€ 17,000	€ 14,000	€ 14,300	€ 10,900	€ 8,900
Application VA as a share of total costs (VA / output price)	29%	28%	26%	26%	24%	22%
Rate of VA (VA / material & overhead costs)	41%	38%	35%	35%	31%	29%
Breakdown of VA by component or activity						
Total VA in system (excl. MEA and Stack)	**26%**	**29%**	**32%**	**31%**	**36%**	**40%**
HGV system integration	3%	4%	5%	4%	6%	6%
Tank	16%	18%	20%	20%	23%	26%
Balance of Plant	6%	7%	7%	7%	7%	8%
Total VA in stack (excl. MEA)	**20%**	**21%**	**22%**	**22%**	**24%**	**25%**
HGV Stack integration	14%	13%	13%	13%	13%	13%
Bipolar Plate	1%	1%	1%	1%	2%	2%
Balance of Stack	5%	6%	7%	7%	9%	10%
Total VA in MEA	**54%**	**51%**	**46%**	**46%**	**40%**	**35%**
ME Assembly	47%	43%	40%	40%	34%	29%
Gas Diffusion Layer	6%	6%	5%	5%	5%	4%
Membrane	1%	1%	1%	1%	1%	1%
Catalyst	0%	0%	0%	0%	0%	1%
Breakdown of total VA by cost category						
Labour cost	16%	17%	19%	18%	20%	22%
Capex cost	57%	56%	53%	54%	51%	48%
Margin	26%	27%	28%	28%	29%	30%
Total	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Notes: numbers may not add up due to rounding of data						

8.4.2.4 Estimated value creation potential for FC systems for trains and light rail

The estimates of the breakdown of value-added for FC systems for trains and light rail under the low and high market scenarios for 2030 are presented in Figure 62 and Figure 63. Under the low scenario, the annual global production volume corresponds to around 80 systems, while around 400 fuel cell systems for trains are produced under a high scenario. The breakdown of value-added creation for all three scenarios, for both 2024 and 2030, can be found in Table 101.

> ***Note:*** *As the underlying cost models assume that fuel cell production for buses, HGVs and trains is based on the same production technology and fuel cell component configuration (catalyst, GDL, MEA, bipolar plated, balance of stack and balance of plant), with overall production learning cost reduction factors reflecting a cumulative effect across these application types, the pattern of GVA creation and intensity is similar across the three application types. Differences arise because of the different size of stacks and tanks used for each application.*

In contrast to road vehicles, hydrogen storage tanks are estimated to generate the largest share of total value-added in the supply chain of fuel cell systems for trains and light rail. This share, which reaches over half of total value-added under the high scenario for 2030, increases over time and at higher production levels. By contrast, the share of value-added generated from MEA activities and associated components (i.e. GDL, membranes and catalyst) decreases with increases in production volumes. Their combined share, which represents 41 percent of total value-added in the low scenario for 2024, is estimated at only 23 percent in the high scenario for 2030. These findings reflect differences in the underlying assumptions for opportunities for overall cost (output price) reductions at higher volumes of production, which are assumed greater for MEAs than for system integration and tanks.

Reflecting the common cost model used, the intensity of value-added creation in the supply chain for fuel cell systems for trains and light rail is essentially the same as for buses and HGVs. Value-added intensity is highest for the balance of stack (70% in the low scenario for 2030 and 67% in the high scenario), followed by MEA activities (50% and 41%) and the GDL (46% in both scenarios).

Although the general breakdown of value-added generation by 'production factor' has the same pattern as for buses and HGVs, the overall share of value-added attributable to capital (capex) is lower for fuel cell systems for trains and light rail. This finding is attributable to differences in the relative share of the fuel cell stack, tank and balance of plant in the overall cost of the fuel cell system for different applications. Specifically, this relates to the high share of tanks (and balance of plant) in overall system costs, which have low capital intensity and higher labour intensity compared to stack integration and MEA activities.

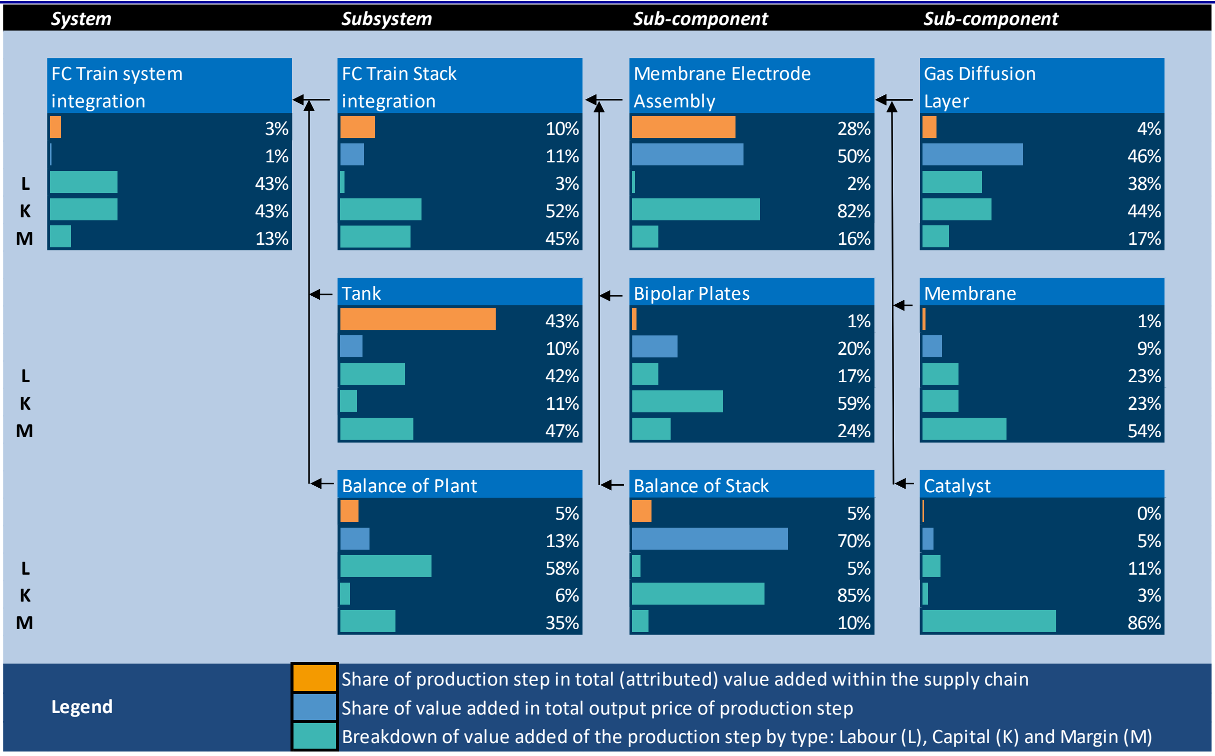


Figure 62: Value-added decomposition for FC system for trains and light rail, low market deployment scenario, 2030

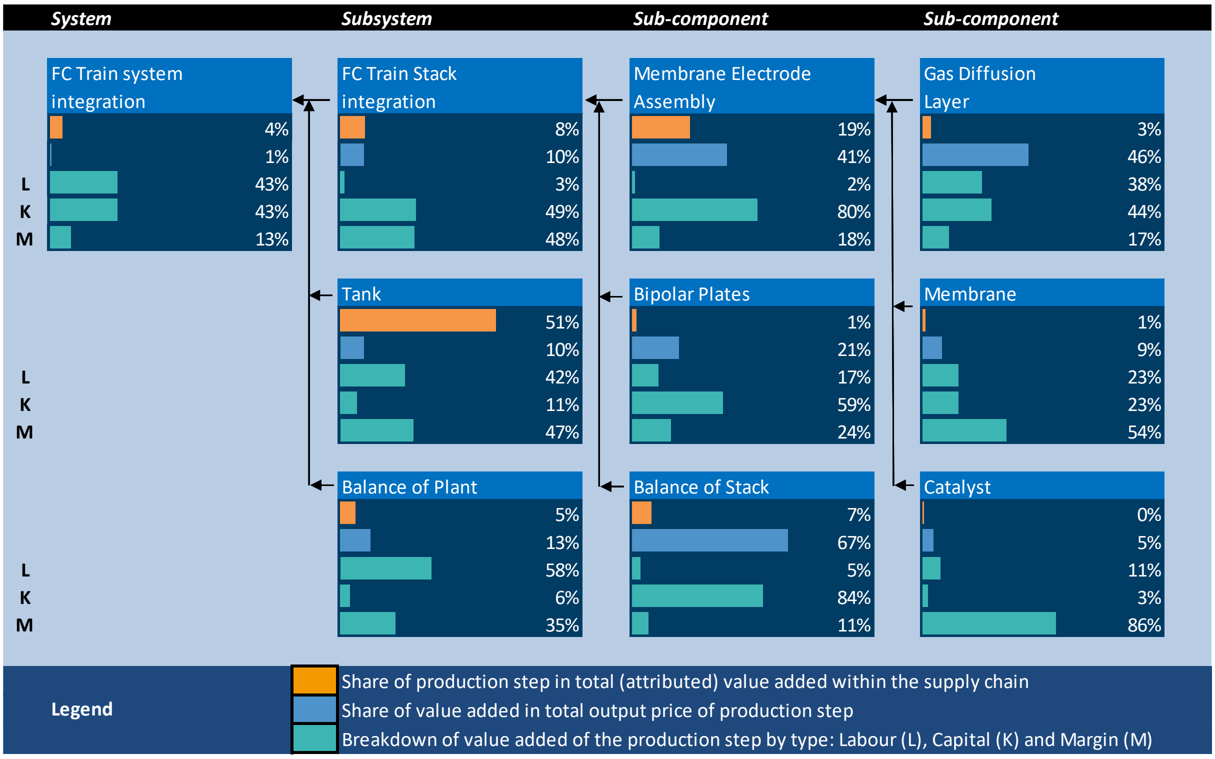


Figure 63: Value-added decomposition for FC system for trains and light rail, high market deployment scenario, 2030

Table 101: Value-added decomposition for FC system for trains and light rail by market deployment scenario, 2024 and 2030

Year	2024			2030		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Units)	30	70	160	80	240	400
Annual production rate of leading manufacturer (MW)	500	800	1,400	1,400	3,000	5,400
System cost (Output price)	€ 206,000	€ 184,000	€ 167,000	€ 168,000	€ 144,000	€ 129,000
Total VA within system	€ 40,900	€ 34,600	€ 29,500	€ 30,100	€ 24,100	€ 20,400
Application VA as a share of total costs (VA / output price)	20%	19%	18%	18%	17%	16%
Rate of VA (VA / material & overhead costs)	25%	23%	21%	22%	20%	19%
Breakdown of VA by component or activity						
Total VA in system (excl. MEA and Stack)	**44%**	**48%**	**52%**	**51%**	**56%**	**61%**
FC Train system integration	3%	3%	3%	3%	4%	4%
Tank	37%	40%	44%	43%	47%	51%
Balance of Plant	5%	5%	5%	5%	5%	5%
Total VA in stack (excl. MEA)	**15%**	**15%**	**15%**	**16%**	**16%**	**16%**
FC Train Stack integration	10%	10%	9%	10%	9%	8%
Bipolar Plate	1%	1%	1%	1%	1%	1%
Balance of Stack	4%	5%	5%	5%	6%	7%
Total VA in MEA	**41%**	**37%**	**33%**	**33%**	**28%**	**23%**
ME Assembly	35%	32%	28%	28%	23%	19%
Gas Diffusion Layer	5%	4%	4%	4%	3%	3%
Membrane	1%	1%	1%	1%	1%	1%
Catalyst	0%	0%	0%	0%	0%	0%
Breakdown of total VA by cost category						
Labour cost	22%	24%	25%	25%	27%	29%
Capex cost	46%	44%	41%	41%	38%	35%
Margin	32%	33%	34%	33%	35%	36%
Total	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Notes: numbers may not add up due to rounding of data						

8.4.2.5 Estimated value creation potential for FC systems for PEM micro-CHPs

The estimates of the breakdown of value-added for FC system for PEM micro-CHPs under the low and high market scenarios for 2030 are presented in Figure 64 and Figure 65. Under the low scenario, the annual global production volume corresponds to around 150 thousand systems, while around 500 thousand fuel cell systems are produced under a high scenario. The breakdown of value-added creation for all three scenarios, for both 2024 and 2030, can be found in Table 102.

A comparison of the low and high scenarios for 2030 reveals only small changes in the distribution of value-added generated within the supply chain, reflecting the fact that production volumes in both scenarios are substantial and scope for further cost reductions from economies of scale are limited. Approximately three-quarters of value-added is generated in the downstream segments of system integration and production of balance of plant items, with system integration representing around two-fifths of total value-added and balance of plant around one-third. There is some shifting of value-added from upstream to downstream supply chain segments, with both membrane assembly activities and the gas diffusion layer accounting for a declining share of total value-added at higher production volumes.

The intensity of value-added generation is highest for balance of stack – 71% in the low scenario for 2030 and 68% in the high scenario – followed by membrane electrode assembly activities (49% in the low scenario) and the gas diffusion layer (46%).

Within the supply chain for FC systems for PEM micro-CHPs, labour and capital (capex) inputs each account for around 40 percent of overall value-added creation. The share of labour is largely driven by production of balance of plant items for system integration and system integration activities themselves, with labour accounting for nearly 60 percent of value-added for balance of plant items and over 40 percent for system integration activities. The share of capital (capex) in value-added generation is highest for membrane assembly activities (85% in both the high and low scenarios for 2030) and balance of stack (84%).

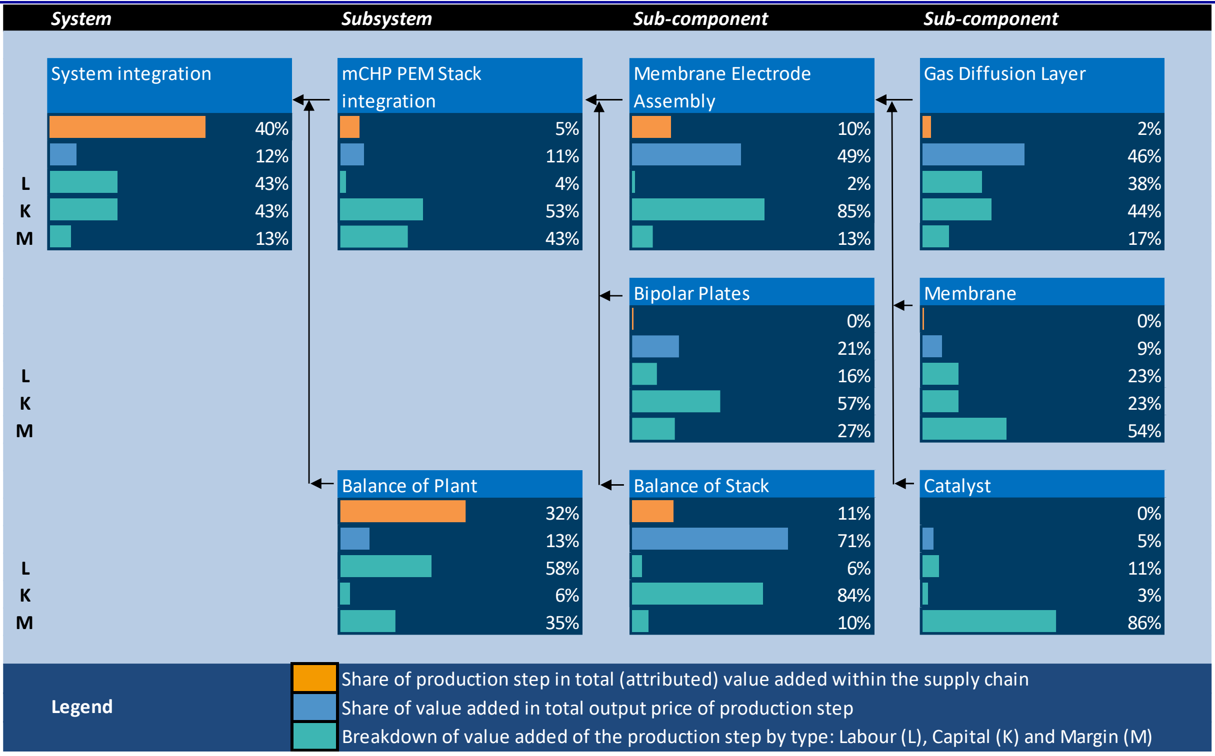


Figure 64: Value-added decomposition for FC system for PEM micro-CHPs, low market deployment scenario, 2030

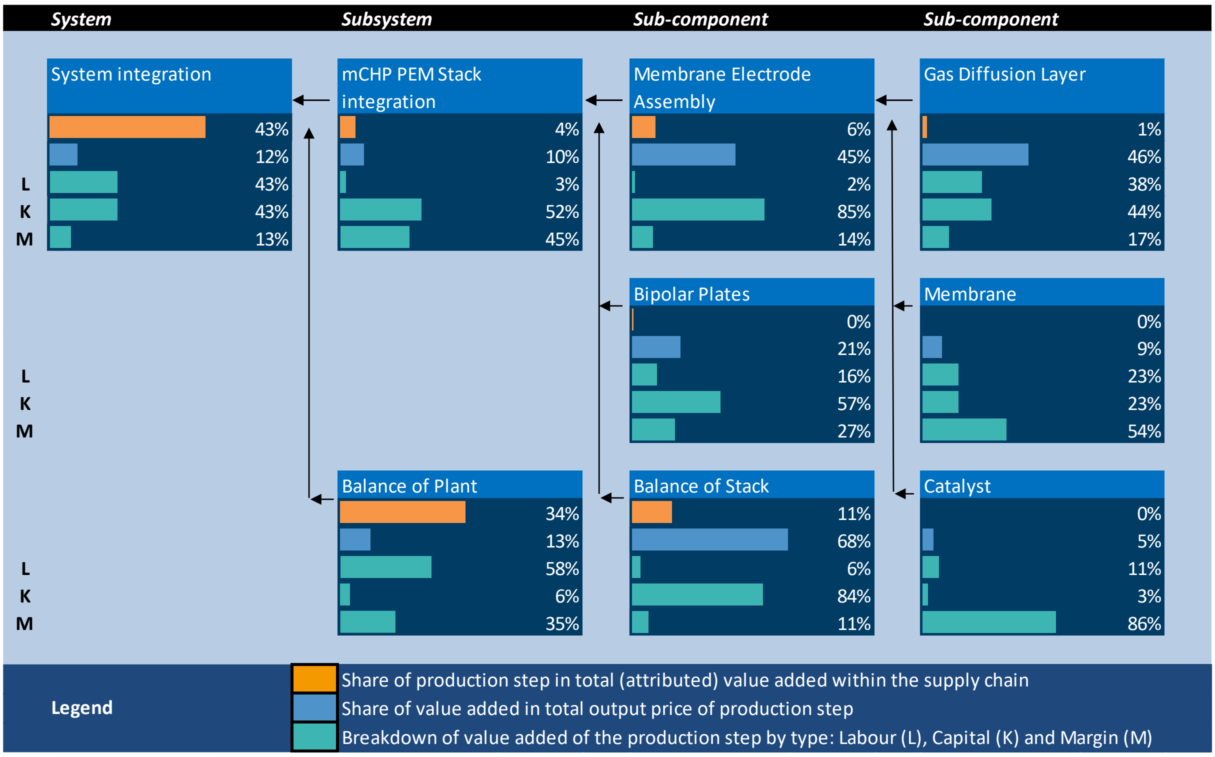


Figure 65: Value-added decomposition for FC system for PEM micro-CHPs, high market deployment scenario, 2030

Table 102: Value-added decomposition for FC system for PEM micro-CHPs by market deployment scenario, 2024 and 2030

Year	2024			2030		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Thousand units)	47	130	169	151	308	505
Annual production rate of leading manufacturer (Thousand units)	28	78	101	91	185	303
System cost (Output price)	€ 2,700	€ 2,400	€ 2,300	€ 2,300	€ 2,200	€ 2,000
Total VA within system	€ 800	€ 700	€ 700	€ 700	€ 600	€ 600
Application VA as a share of total costs (VA / output price)	31%	30%	30%	30%	29%	29%
Rate of VA (VA / material & overhead costs)	46%	44%	43%	43%	42%	41%
Breakdown of VA by component or activity						
Total VA in system (excl. MEA and Stack)	**65%**	**70%**	**71%**	**72%**	**75%**	**77%**
PEM micro-CHP system integration	36%	39%	39%	40%	41%	43%
Balance of Plant	29%	31%	32%	32%	33%	34%
Total VA in stack (excl. MEA)	**16%**	**16%**	**16%**	**16%**	**15%**	**15%**
PEM micro-CHP stack integration	6%	5%	5%	5%	4%	4%
Bipolar Plate	0%	0%	0%	0%	0%	0%
Balance of Stack	10%	10%	10%	11%	11%	11%
Total VA in MEA	**19%**	**15%**	**13%**	**12%**	**10%**	**8%**
ME Assembly	15%	12%	11%	10%	8%	6%
Gas Diffusion Layer	4%	3%	2%	2%	2%	1%
Membrane	0%	0%	0%	0%	0%	0%
Catalyst	0%	0%	0%	0%	0%	0%
Breakdown of total VA by cost category						
Labour cost	35%	37%	38%	38%	39%	40%
Capex cost	44%	41%	41%	40%	39%	38%
Margin	21%	22%	22%	22%	22%	22%
Total	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Notes: numbers may not add up due to rounding of data						

8.4.2.6 Estimated value creation potential for FC systems for PEM CHPs

The estimates of the breakdown of value-added for FC system for PEM CHPs under the low and high market scenarios for 2030 are presented in Figure 66 and Figure 67. Under the low scenario, the annual global production volume corresponds to around 3,300 systems, while around 21,000 thousand fuel cell systems are produced under a high scenario. The breakdown of value-added creation for all three scenarios, for both 2024 and 2030, can be found in Table 103.

The pattern of value-added generation is like that estimated for PEM micro-CHP systems, although the share of value-added generated by balance of stack items for large systems is minimal, whereas it is estimated at around 10% for micro systems. This is offset by an even higher share of value-added generated in the downstream segments, with system integration and production of balance of plant items reaching a combined share over 90 percent in both scenarios. System integration alone reaches half of total value-added generated in the supply chain.

The intensity of value-added creation is highest for membrane electrode assembly activities, together with balance of stack and the gas diffusion layer, though neither of the latter two segments make a measurable contribution to overall value-added creation in the supply chain.

Labour contributes around 45 percent of total value-added generated in the PEM CHP supply chain, which is higher than for PEM micro-CHPs. The capital (capex) share is around one third. As with micro-CHPs, the high share of labour is largely driven by production of balance of plant items for system integration and system integration activities themselves, with labour accounting for over half of value-added for balance of plant items and over 40 percent for system integration activities. The share of capital (capex) in value-added generation is highest for membrane assembly activities and balance of stack.

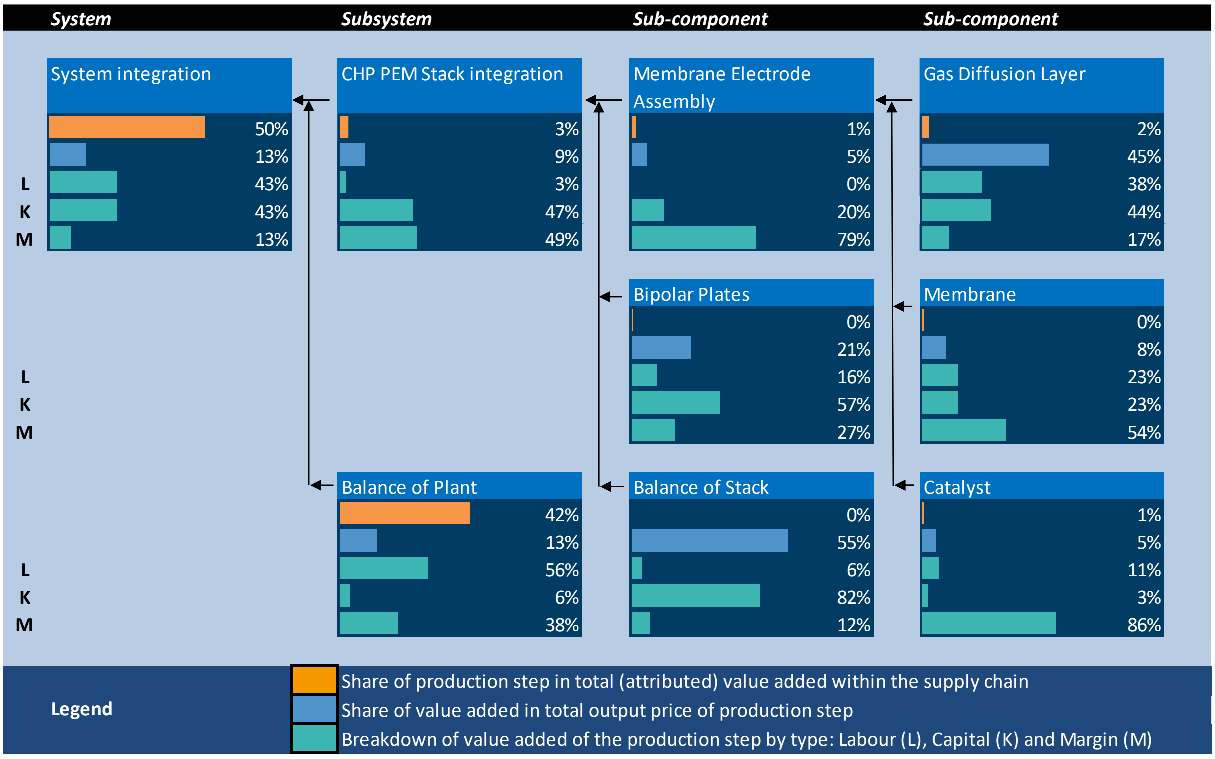


Figure 66: Value-added decomposition for FC system for PEM CHPs, low market deployment scenario, 2030

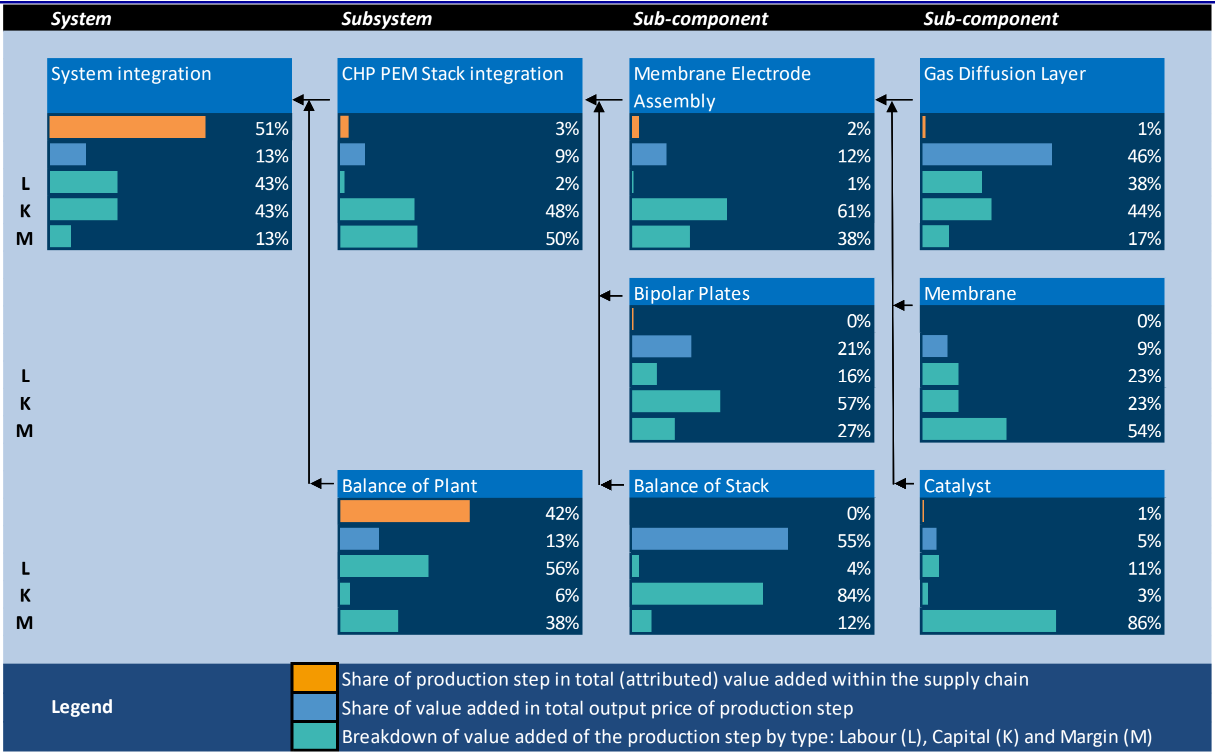


Figure 67: Value-added decomposition for FC system for PEM CHPs, high market deployment scenario, 2030

Table 103: Value-added decomposition for FC system for PEM CHPs by market deployment scenario, 2024 and 2030

Year	2024			2030		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Units)	900	1,600	5,300	3,300	9,000	21,000
Annual production rate of leading manufacturer (Units)	500	900	3,200	2,000	5,400	12,600
System cost (Output price)	€ 214,000	€ 200,000	€ 178,000	€ 184,000	€ 170,000	€ 158,000
Total VA within system	€ 56,000	€ 51,000	€ 45,400	€ 45,600	€ 42,700	€ 39,700
Application VA as a share of total costs (VA / output price)	26%	26%	26%	25%	25%	25%
Rate of VA (VA / material & overhead costs)	35%	34%	34%	33%	34%	34%
Breakdown of VA by component or activity						
Total VA in system (excl. MEA and Stack)	**83%**	**88%**	**91%**	**93%**	**92%**	**93%**
PEM micro-CHP system integration	45%	48%	50%	50%	50%	51%
Balance of Plant	38%	40%	42%	42%	42%	42%
Total VA in stack (excl. MEA)	**5%**	**4%**	**3%**	**3%**	**3%**	**3%**
PEM micro-CHP stack integration	4%	4%	3%	3%	3%	3%
Bipolar Plate	0%	0%	0%	0%	0%	0%
Balance of Stack	0%	0%	0%	0%	0%	0%
Total VA in MEA	**12%**	**8%**	**5%**	**4%**	**5%**	**4%**
ME Assembly	8%	5%	3%	1%	3%	2%
Gas Diffusion Layer	4%	3%	2%	2%	1%	1%
Membrane	0%	0%	0%	0%	0%	0%
Catalyst	0%	1%	1%	1%	1%	1%
Breakdown of total VA by cost category						
Labour cost	43%	45%	46%	47%	46%	46%
Capex cost	32%	30%	28%	27%	28%	28%
Margin	25%	25%	26%	26%	25%	25%
Total	100%	100%	100%	100%	100%	100%
Notes: numbers may not add up due to rounding of data						

8.4.2.7 Estimated value creation potential for PEM electrolyser systems

The estimates of the breakdown of value-added for PEM electrolysers under the low and high market scenarios for 2030 are presented in Figure 68 and Figure 69. Under the low scenario, the annual global production volume corresponds to around 700 systems (900 MW), while the high scenario corresponds to annual production of around 3,200 systems (4,000 MW). The breakdown of value-added creation for all three scenarios, for both 2024 and 2030, is shown in Table 104.

The estimates indicate that the generation of value-added is concentrated in three downstream production segments, namely system integration at just below 50 percent of total value-added generated in the supply chain, balance of plant at just below 20 percent, and stack integration, at around 15 percent. Overall, these segments account for more than four-fifths of value-added generated in the supply chain. This pattern shows limited variation across the scenarios and when comparing 2024 and 2030 estimates.

In terms of the intensity of value-added generation, the highest rates are observed in more upstream segments, particularly balance of stack component – for which value-added is estimated at 54% of the cost price in 2030 for both the low and high scenarios – and porous layers (44%). However, these components represent, respectively, only 7% and 2% of the total value-added generated in the supply chain.

The share of value-added generation by each 'production factor' is relatively stable across time and scenarios. Labour inputs account for around a third of total value-added generation and capital inputs (capex) for just below 45 percent. For 2030, the share of labour in total value-added generation is highest in balance of plant for system integration (58%), system integration (43%) and the porous layer (40%). Conversely, the share of capital dominates for balance of stack components (84%), stack integration (62-64%) and membrane electrode assembly activities (61%).

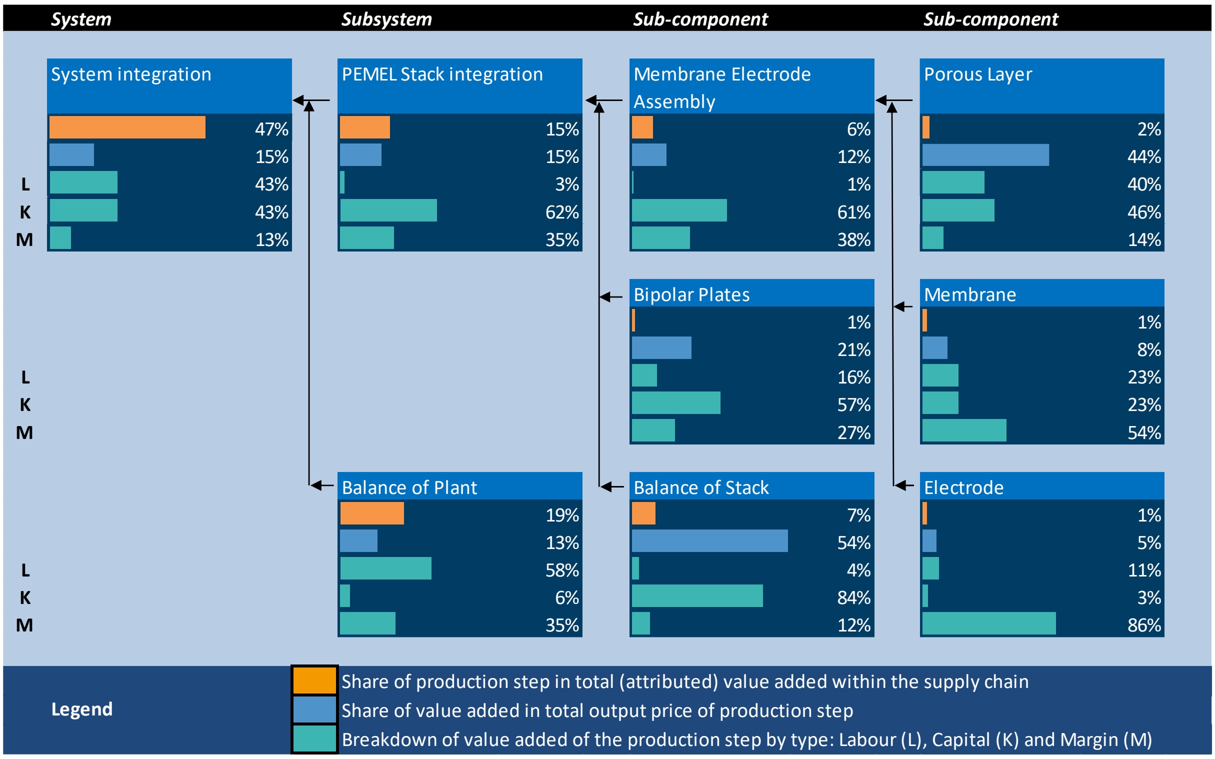


Figure 68: Value-added decomposition for PEM electrolyser systems, low market deployment scenario, 2030

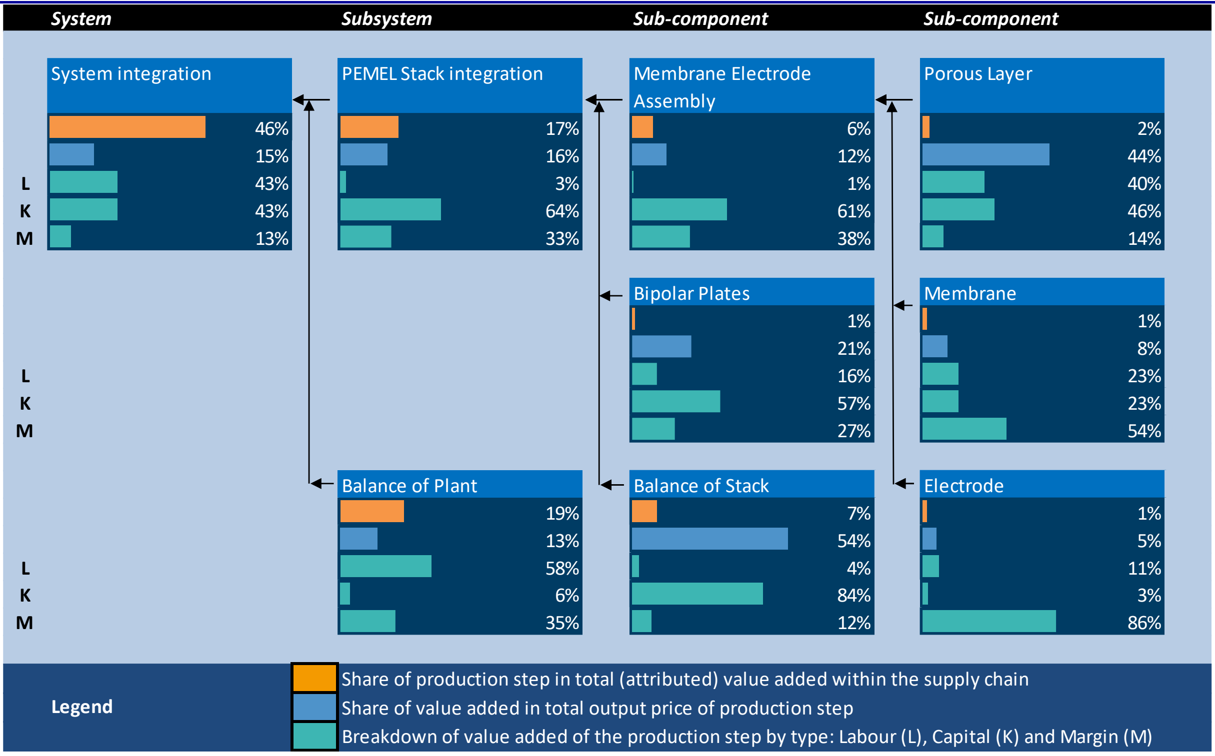


Figure 69: Value-added decomposition for PEM electrolyser systems, high market deployment scenario, 2030

Table 104: Value-added decomposition for PEM electrolyser systems by market deployment scenario, 2024 and 2030

Year	2024			2030		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Units)	300	650	1,050	700	1,600	3,250
Annual production rate of leading manufacturer (Units)	200	400	650	450	950	1,950
System cost (Output price)	€ 335,000	€ 314,000	€ 303,000	€ 311,000	€ 295,000	€ 282,000
Total VA within system	€ 104,000	€ 103,000	€ 100,000	€ 102,000	€ 98,000	€ 94,000
Application VA as a share of total costs (VA / output price)	31%	33%	33%	33%	33%	33%
Rate of VA (VA / material & overhead costs)	45%	49%	49%	49%	49%	50%
Breakdown of VA by component or activity						
Total VA in system (excl. MEA and Stack)	**70%**	**67%**	**66%**	**67%**	**66%**	**64%**
PEMEL system integration	50%	47%	47%	47%	47%	46%
Balance of Plant	20%	19%	19%	19%	19%	19%
Total VA in stack (excl. MEA)	**17%**	**23%**	**24%**	**23%**	**24%**	**25%**
PEMEL Stack integration	8%	15%	16%	15%	16%	17%
BPP	1%	1%	1%	1%	1%	1%
Balance of Stack	8%	7%	7%	7%	7%	7%
Total VA in MEA	**14%**	**10%**	**10%**	**10%**	**10%**	**10%**
ME Assembly	8%	6%	6%	6%	6%	6%
GDL	3%	2%	2%	2%	2%	2%
Membrane	1%	1%	1%	1%	1%	1%
Catalyst	1%	1%	1%	1%	1%	1%
Breakdown of total VA by cost category						
Labour cost	36%	34%	34%	34%	33%	33%
Capex cost	39%	43%	43%	43%	43%	44%
Margin	25%	23%	23%	23%	23%	23%
Total	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Notes: numbers may not add up due to rounding of data						

8.4.2.8 Estimated value creation potential for FC systems for SOFC micro-CHPs

The estimates of the breakdown of value-added for SOFC micro-CHP systems under the low and high market scenarios for 2030 are presented in Figure 70 and Figure 71. Under the low scenario, the annual global production volume corresponds to around 225 thousand systems, while the high scenario corresponds to annual production of around 760 thousand systems. The breakdown of value-added creation for all three scenarios, for both 2024 and 2030, is shown in Table 105.

A comparison of the low and high scenarios for 2030 reveals relatively small changes in the distribution of value-added generated within the supply chain. Most value-added is generated in the supply of balance of plant components for system integration, which accounts for 55 percent of value-added in the low scenario for 2030 and over 60 percent in the high scenario. Balance of stack items account for a further 15 percent of value-added generated in the supply chain under both scenarios. In contrast to PEM micro-CHP systems, system integration activities account for only a small proportion of value-added generated in the supply chain, falling to only 3 percent in the high scenario for 2030. The share of value-added generated though the production of cells (EEA, MEA) is estimated at just below 15 percent.

The intensity of value-added creation is highest for cells, balance of stack items, interconnectors and seals, reaching or exceeding 50 percent for all these segments. More than half of the VA generated in the supply chain of SOFC micro-CHP systems is attributed to labour inputs, with value-added attributed to capital (capex) is estimated in the range of 16 to 18 percent. Labour intensity is relatively high for many segments, for example, seals (86% in the high scenario for 2030), system integration (66%), porous layer (62%).

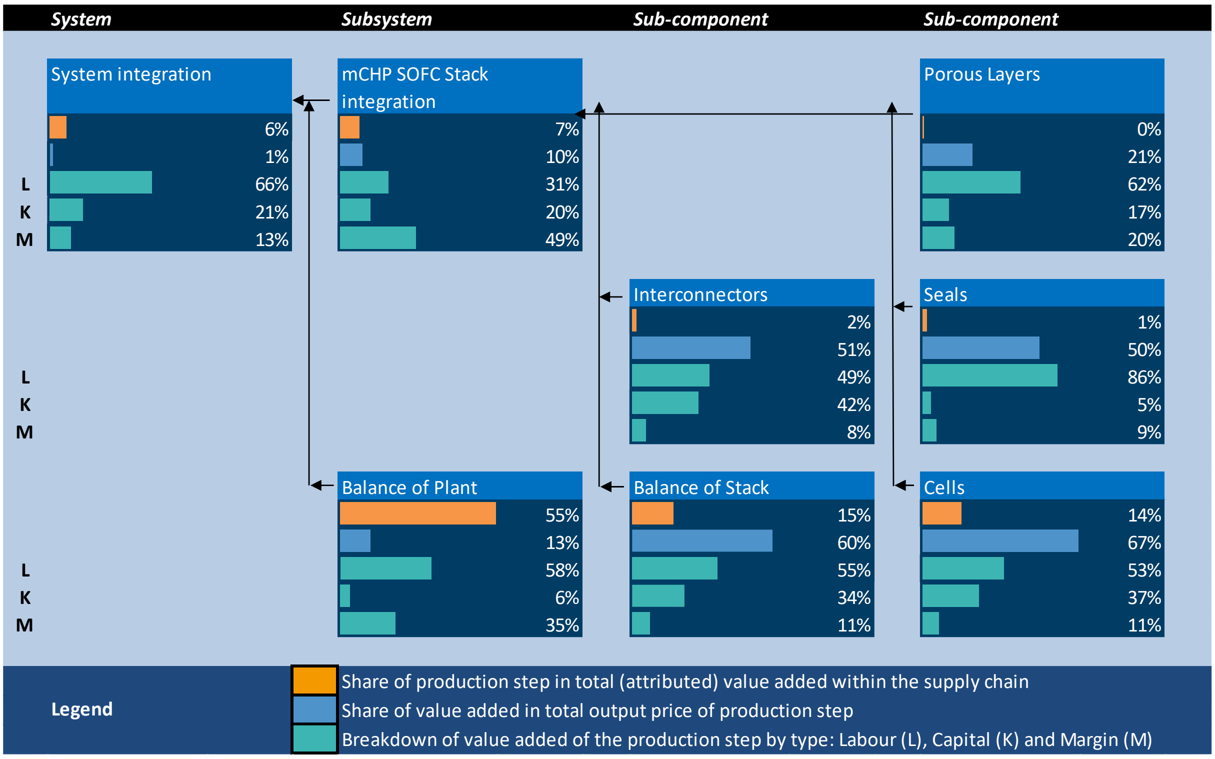


Figure 70: Value-added decomposition for FC system for SOFC micro-CHPs, low market deployment scenario, 2030

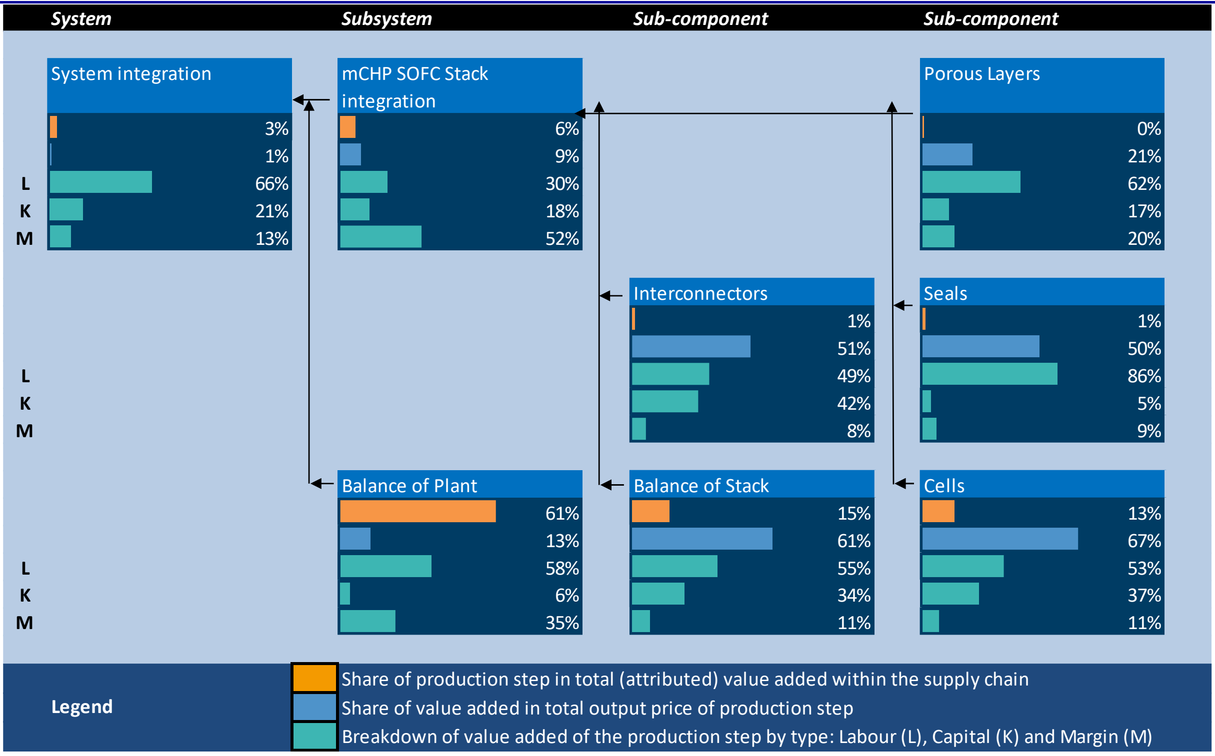


Figure 71: Value-added decomposition for FC system for SOFC micro-CHPs, high market deployment scenario, 2030

Table 105: Value-added decomposition for FC system for SOFC micro-CHPs by market deployment scenario, 2024 and 2030

Year	2024			2030		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Thousand units)	70	195	255	225	460	760
Annual production rate of leading manufacturer (Thousand units)	45	115	150	135	275	455
System cost (Output price)	€ 3,800	€ 3,700	€ 3,600	€ 3,700	€ 3,500	€ 3,400
Total VA within system	€ 800	€ 700	€ 700	€ 700	€ 700	€ 700
Application VA as a share of total costs (VA / output price)	0%	0%	0%	0%	0%	0%
Rate of VA (VA / material & overhead costs)	26%	25%	25%	25%	23%	23%
Breakdown of VA by component or activity						
Total VA in system (excl. Stack)	**60%**	**61%**	**61%**	**61%**	**65%**	**64%**
SOFC micro-CHP system integration	7%	6%	5%	6%	4%	3%
Balance of Plant	53%	55%	56%	55%	61%	61%
Total VA in stack (excl. Cells)	**26%**	**25%**	**25%**	**25%**	**22%**	**23%**
SOFC micro-CHP stack integration	7%	7%	7%	7%	4%	6%
Porous Layer	1%	0%	0%	0%	0%	0%
Seals	1%	1%	1%	1%	1%	1%
Interconnectors	2%	2%	2%	2%	2%	1%
Balance of Stack	15%	15%	15%	15%	15%	15%
Cells (EEA, MEA)	**14%**	**14%**	**14%**	**14%**	**14%**	**13%**
Breakdown of total VA by cost category						
Labour cost	56%	56%	56%	56%	56%	56%
Capex cost	18%	17%	17%	17%	16%	16%
Margin	27%	27%	27%	27%	28%	28%
Total	100%	100%	100%	100%	100%	100%
Notes: numbers may not add up due to rounding of data						

8.4.2.9 Estimated value creation potential for FC systems for SOFC CHPs

The estimates of the breakdown of value-added for SOFC CHP systems under the low and high market scenarios for 2030 are presented in Figure 72 and Figure 73. Under the low scenario, the annual global production volume corresponds to around 3,300 systems, while the high scenario corresponds to annual production of around 21,000 systems. The breakdown of value-added creation for all three scenarios, for both 2024 and 2030, is shown in Table 106.

In contrast to SOFC micro-CHPs, the generation of value-added for larger CHP systems is more evenly distributed through the supply chain, with both upstream and downstream segments making a notable contribution. Cell production is estimated to account for around a quarter of value-added generation in all scenarios, for both 2024 and 2030. The second highest share of value-added is attributed to balance of plant items for system integration, at around a fifth of total value-added generated in the supply chain. The combined share of system integration and stack integration activities is just below 30 percent.

As is the case for the supply chain for SOFC micro-CHP systems, the intensity of value-added creation is highest for cells (65%), balance of stack items (59%), interconnectors (50%) and seals (49%), though interconnectors and seals generate only small shares of total value-added. Again, more than half of the VA generated in the supply chain is attributed to labour inputs, with value-added attributed to capital (capex) is estimated in just below a quarter.

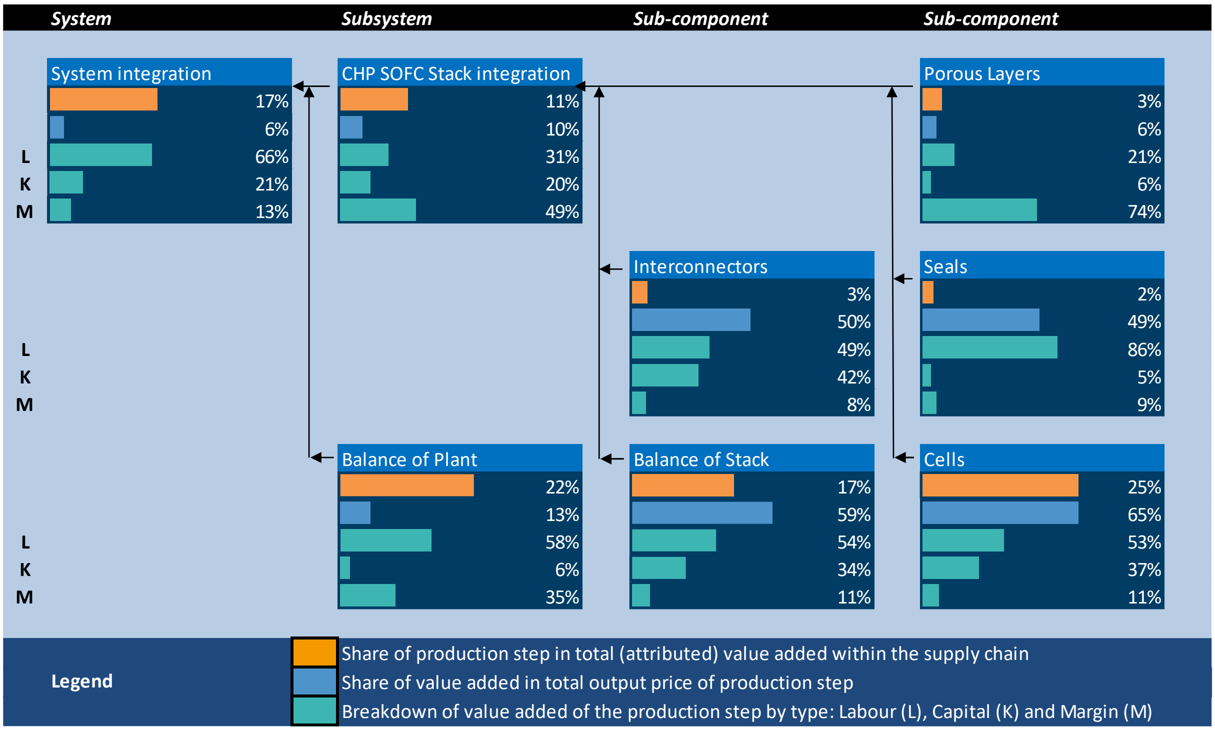


Figure 72: Value-added decomposition for FC system for SOFC CHPs, low market deployment scenario, 2030

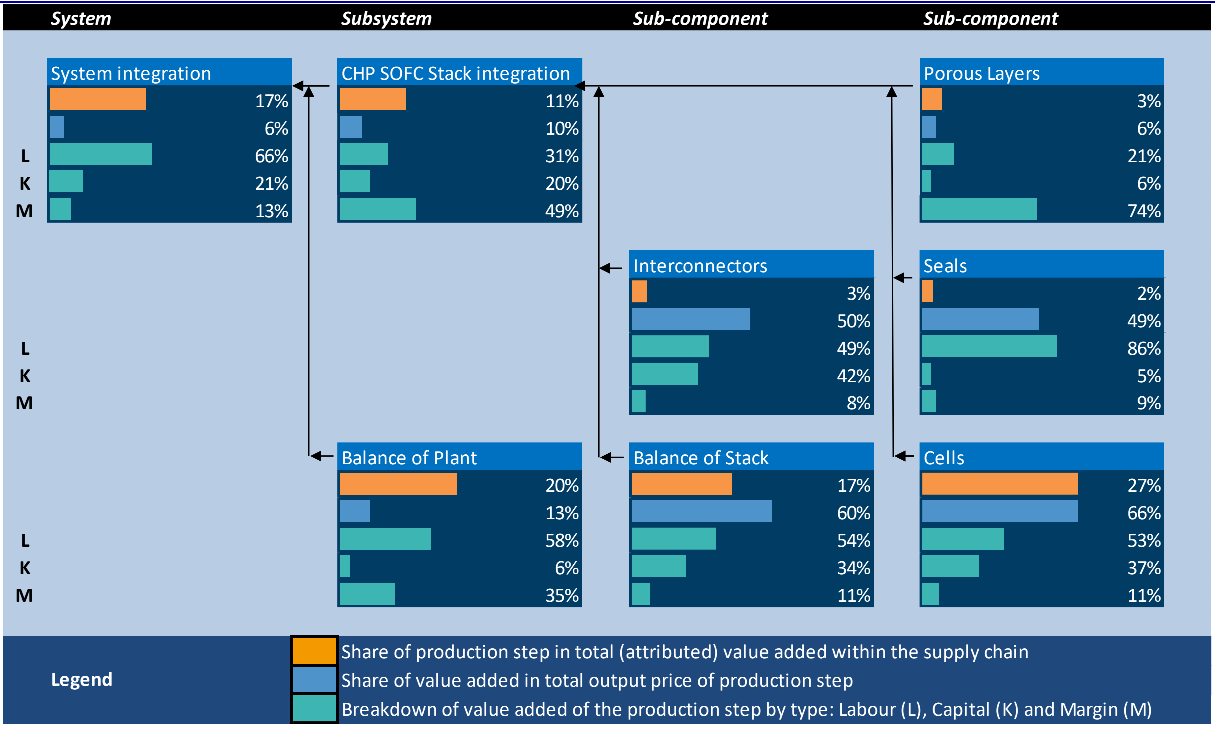


Figure 73: Value-added decomposition for FC system for SOFC CHPs, high market deployment scenario, 2030

Table 106: Value-added decomposition for FC system for SOFC CHPs by market deployment scenario, 2024 and 2030

Year	2024			2030		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Units)	900	1,600	5,300	3,300	9,000	21,000
Annual production rate of leading manufacturer (Units)	500	900	3,200	2,000	5,400	12,600
System cost (Output price)	€ 131,000	€ 126,000	€ 118,000	€ 121,000	€ 115,000	€ 110,000
Total VA within system	€ 41,700	€ 40,600	€ 39,100	€ 39,700	€ 38,600	€ 37,700
Application VA as a share of total costs (VA / output price)	32%	32%	33%	33%	34%	34%
Rate of VA (VA / material & overhead costs)	47%	48%	50%	49%	50%	52%
Breakdown of VA by component or activity						
Total VA in system (excl. Stack)	**41%**	**40%**	**39%**	**39%**	**38%**	**37%**
SOFC CHP system integration	18%	18%	17%	17%	17%	17%
Balance of Plant	23%	23%	21%	22%	21%	20%
Total VA in stack (excl. Cells)	**34%**	**35%**	**35%**	**35%**	**36%**	**37%**
SOFC CHP stack integration	11%	11%	11%	11%	11%	11%
Porous Layer	3%	3%	3%	3%	3%	3%
Seals	2%	2%	2%	2%	2%	2%
Interconnectors	3%	3%	3%	3%	3%	3%
Balance of Stack	16%	16%	17%	17%	17%	17%
Cells (EEA, MEA)	**25%**	**25%**	**26%**	**25%**	**26%**	**27%**
Breakdown of total VA by cost category						
Labour cost	54%	54%	53%	53%	53%	53%
Capex cost	23%	23%	24%	24%	24%	24%
Margin	23%	23%	23%	23%	23%	23%
Total	100%	100%	100%	100%	100%	100%
Notes: numbers may not add up due to rounding of data						

8.4.2.10 Estimated value creation potential for Solid Oxide electrolyser systems

The estimates of the breakdown of value-added for Solid Oxide electrolysers (SOEL) under the low and high market scenarios for 2030 are presented in Figure 74 and Figure 75. Under the low scenario, the annual global production volume corresponds to around 90 systems (45 MW total capacity), while the high scenario corresponds to annual production of around 400 systems (200 MW total capacity). The breakdown of value-added creation for all three scenarios, for both 2024 and 2030, is shown in Table 107.

The estimates indicate a very stable pattern over time and across scenarios in the distribution of value-added generated in the supply chain for SO electrolysers, reflecting the fact that low production volumes offer limited scope for cost changes arising from economies of scale. In common with SOFC CHPs, the generation of value-added for SOEL systems is relatively evenly distributed across upstream and downstream supply chain segments. Cell production and balance of plant items for system integration are each estimated to account for around a quarter of value-added generation in all scenarios, for both 2024 and 2030. The combined share of system integration and stack integration activities is just below 30 percent, of which 20 percent coming from system integration and 10 percent from stack integration.

As is the case for the supply chain for SOFC CHP systems – both micro and large – the intensity of value-added creation is highest for cells, balance of stack items, interconnectors and seals. Again, more than half of the VA generated in the supply chain is attributed to labour inputs, with value-added attributed to capital (capex) is estimated in just below a quarter. The labour share in value-added is highest for seals, the porous layer, and system integration.

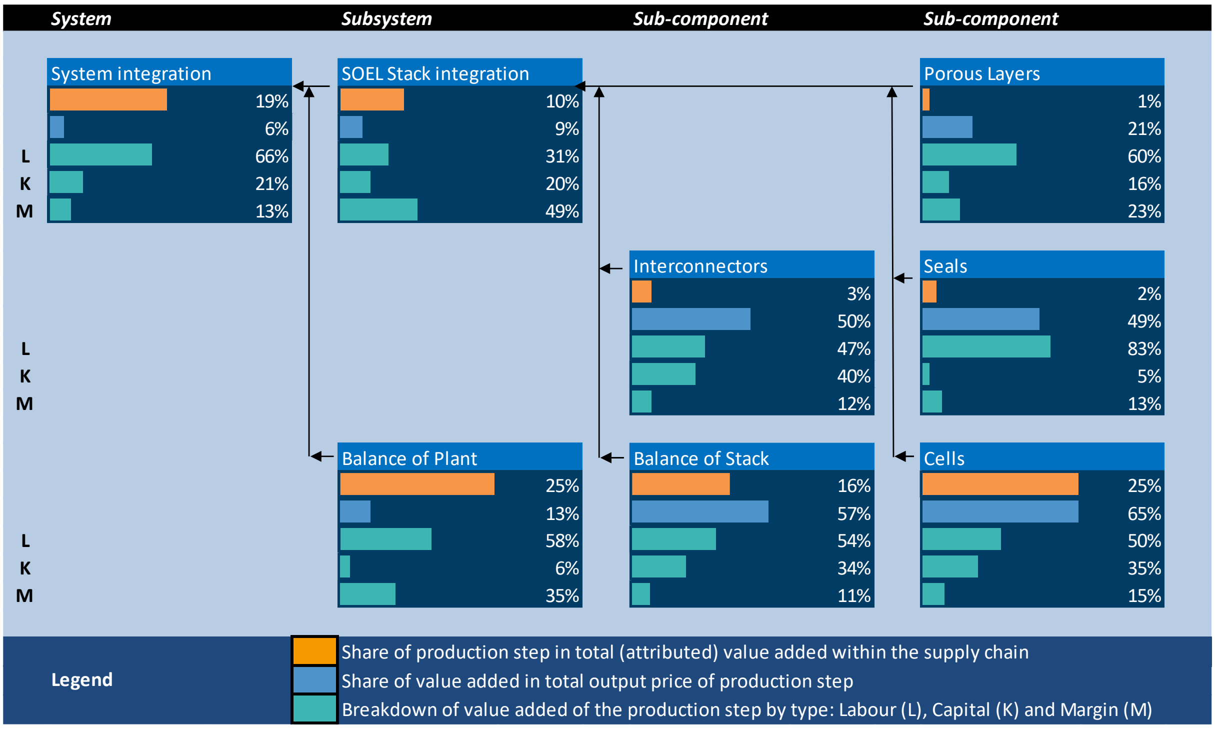


Figure 74: Value-added decomposition for Solid Oxide Electrolyser systems, low market deployment scenario, 2030

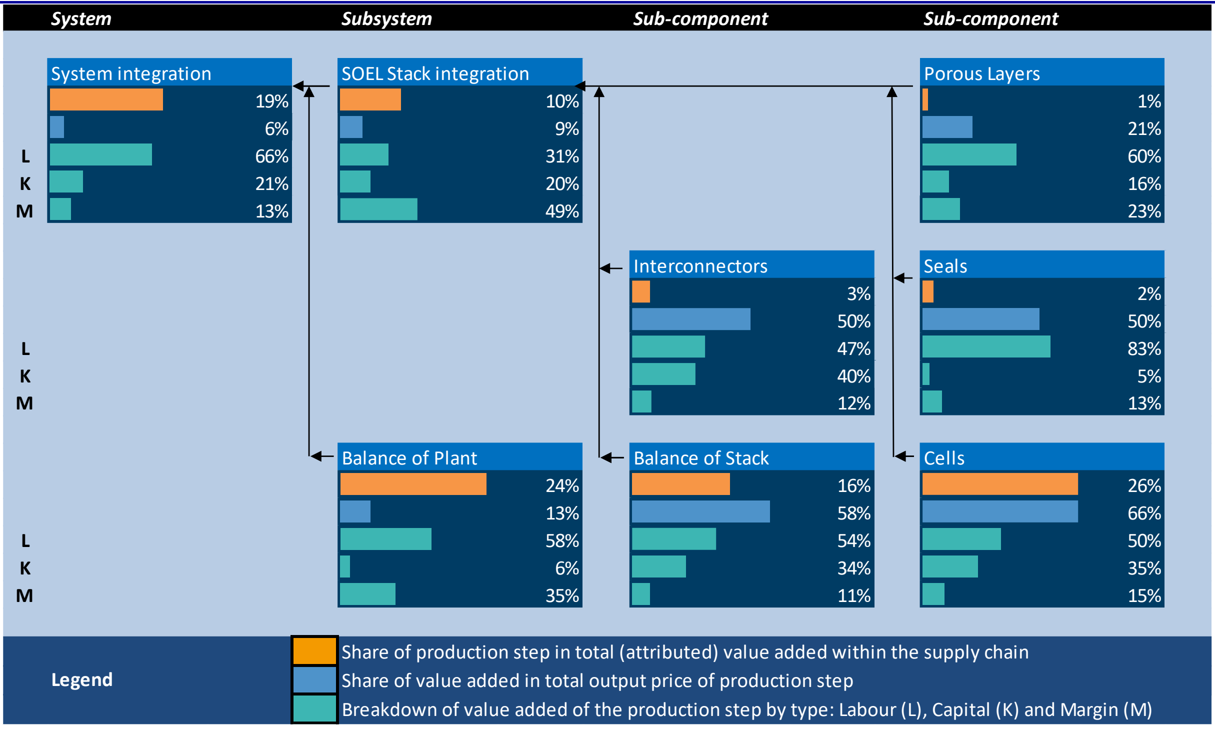


Figure 75 Value-added decomposition for Solid Oxide Electrolyser systems, high market deployment scenario, 2030

Table 107: Value-added decomposition for Solid Oxide Electrolyser systems by market deployment scenario, 2024 and 2030

Year	2024			2030		
Deployment scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total annual production (Units)	40	80	130	90	200	405
Annual production rate of leading manufacturer (Units)	25	50	80	55	120	245
System cost (Output price)	€ 802,000	€ 748,000	€ 719,000	€ 742,000	€ 698,000	€ 664,000
Total VA within system	€ 248,000	€ 232,000	€ 224,000	€ 230,000	€ 219,000	€ 211,000
Application VA as a share of total costs (VA / output price)	31%	31%	31%	31%	31%	32%
Rate of VA (VA / material & overhead costs)	45%	45%	45%	45%	46%	46%
Breakdown of VA by component or activity						
Total VA in system (excl. Stack)	**43%**	**43%**	**43%**	**43%**	**43%**	**43%**
SOEL system integration	18%	19%	19%	19%	19%	19%
Balance of Plant	24%	25%	25%	25%	24%	24%
Total VA in stack (excl. Cells)	**33%**	**32%**	**32%**	**32%**	**32%**	**32%**
SOEL stack integration	10%	10%	10%	10%	10%	10%
Porous Layer	1%	1%	1%	1%	1%	1%
Seals	3%	2%	2%	2%	2%	2%
Interconnectors	3%	3%	3%	3%	3%	3%
Balance of Stack	16%	16%	16%	16%	16%	16%
Cells (EEA, MEA)	**25%**	**25%**	**25%**	**25%**	**25%**	**26%**
Breakdown of total VA by cost category						
Labour cost	55%	55%	54%	55%	54%	54%
Capex cost	23%	23%	23%	23%	23%	23%
Margin	22%	22%	22%	22%	22%	22%
Total	100%	100%	100%	100%	100%	100%
Notes: numbers may not add up due to rounding of data						

8.4.2.11 Estimated value creation potential for hydrogen refuelling stations

The estimates of the breakdown of value-added for hydrogen refuelling stations (HRS) under the low and high market scenarios for 2030 are presented in Figure 76 and Figure 77. Under the low scenario, the annual global production volume corresponds to around 670 stations (520 t/day of new capacity), while the high scenario corresponds to annual production of around 3,700 stations (2,700 t/day of new capacity).

***Note 1:** As opposed to all other applications covered in supply chain value-added estimates, which cover fuel cell systems only, the estimates for hydrogen refuelling stations cover the total costs and corresponding value-added for the installation of the station. This approach explains the predominance of station integration in the supply chain estimates for hydrogen refuelling stations.*

***Note 2:** The estimates for the breakdown of value-added in the supply chain for hydrogen refuelling stations is based on an assumed typical configuration but in reality this will be influenced by the distribution of different sizes of stations (e.g. delivery capacity of hydrogen on a daily basis).*

For HRS, the major part of values-added is generated by station integration, which covers construction and equipment installation, estimated at around 70 percent of total value-added generated. In addition, balance of plant, covering non-specified equipment, accounts for above 10 of total value-added. The two specified items, namely dispensers and compression units are estimated to each generate between 8 to 10 percent of value-added associated to the development of HRS. Since materials and equipment inputs have a relatively low share in overall costs for the construction and installation of HRS, the station integration segment is associated with a high value-added intensity, of close to 90 percent. Each of the three component categories (dispensers, compression units and balance of plant) are estimated to have a high share of labour in generation of value-added, at between 55 to 60 percent.

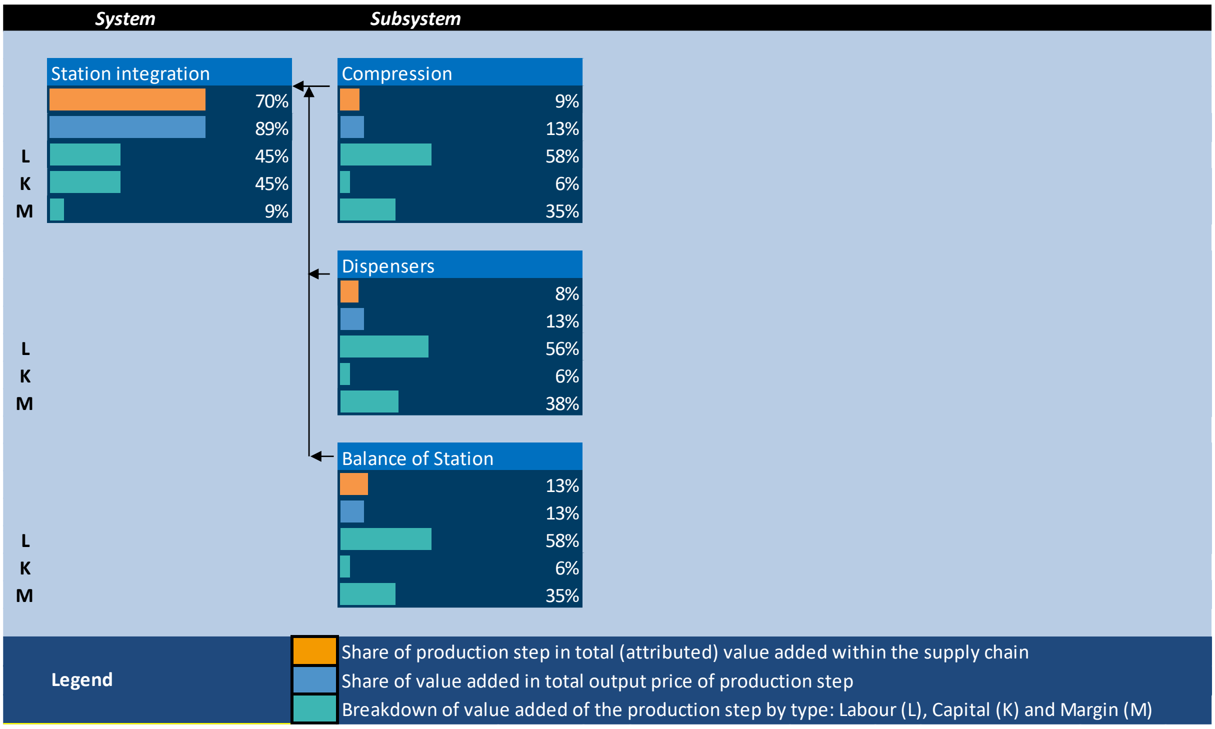


Figure 76: Value-added decomposition for hydrogen refuelling stations, low market deployment scenario, 2030

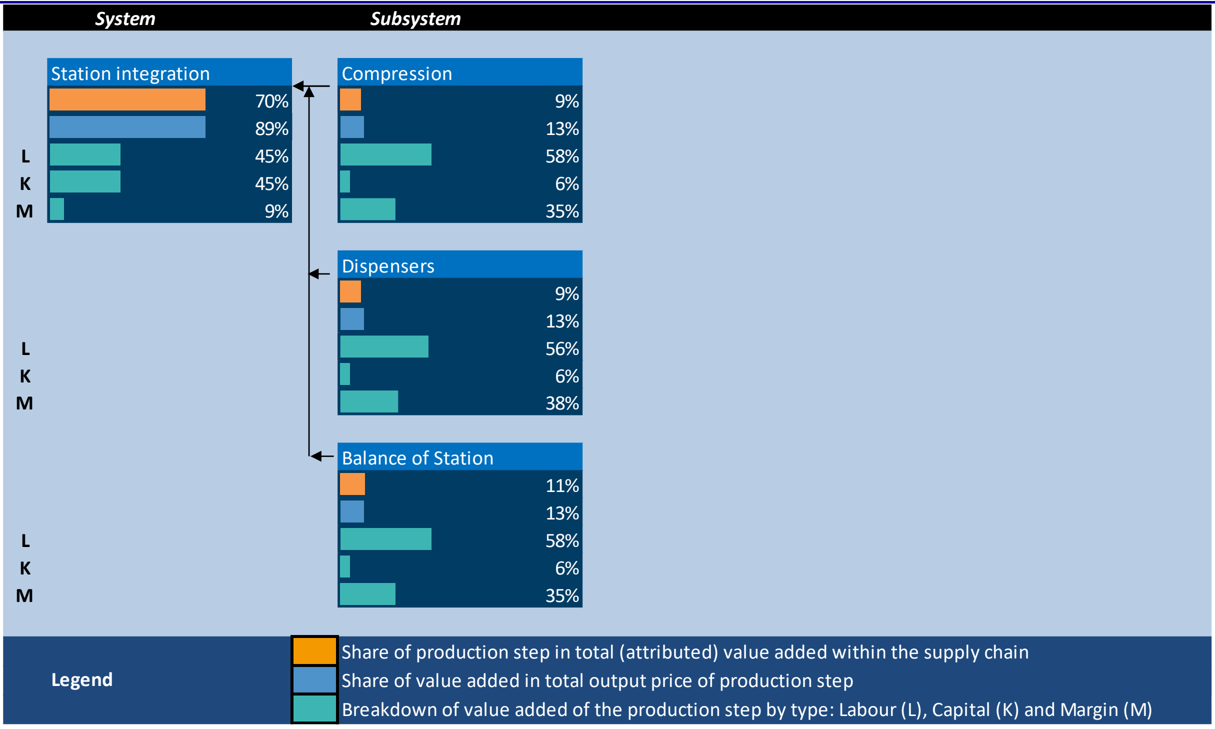


Figure 77: Value-added decomposition for hydrogen refuelling stations, high market deployment scenario, 2030

8.5 Industry scenarios

Industry scenarios were developed for eight down-selected applications. The industry scenarios lay out possible futures of the European FCH value chain, exploring what could happen in the future and what the implications of these possible futures might be. The scenarios are not intended to be 'normative' in the sense that they do not set out an ideal or expected outcome. Rather they serve as a framework for assessing the socio-economic impacts of possible futures with more or less developed European FCH value chains. This assessment can then provide insight into the conditions that may be necessary to maximize the European socio-economic benefits of the FCH value chain.

Two key parameters are varied in the scenarios: 1) the extent of deployment of FCH technologies, and 2) the share of FCH production that is captured by EU actors. The three scenarios are shown graphically in Figure 78.

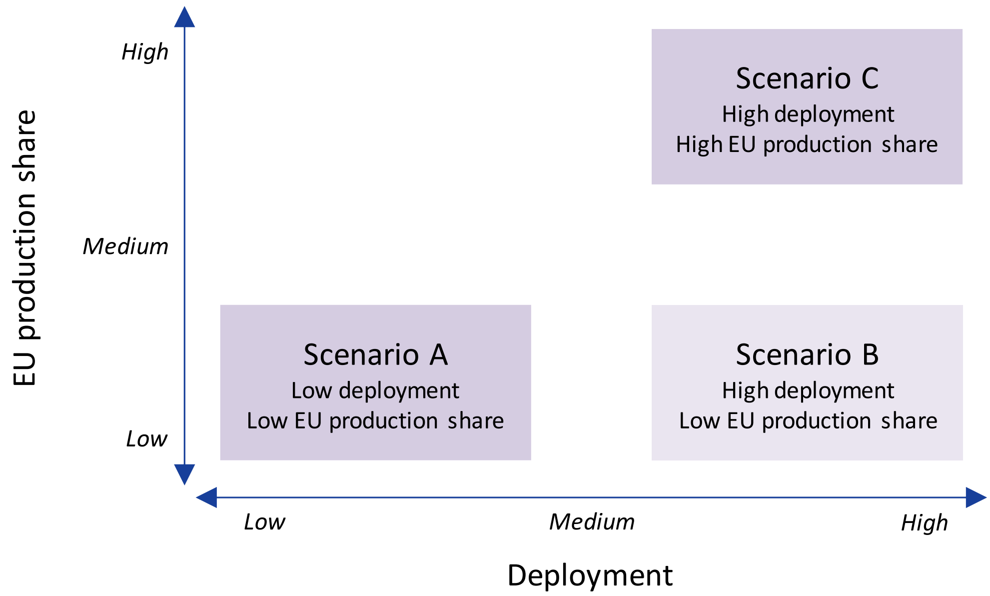


Figure 78: Industry scenario summary

In Scenario A, global and EU deployment of FCH technologies is assumed to be low while for Scenarios B and C, that deployment is assumed to be high. In Scenarios A and B EU actors capture a low production share of the global FCH market, primarily as specialty producers of subsystems and components. Whereas in Scenario C, EU actors capture a higher share of production including capturing a more significant role in system integration for some applications.

A more detailed description of how Scenarios A and C might manifest is given in the subsections below for each of the applications for which detailed value analysis was conducted. These scenario descriptions were validated in a workshop with industry and EC experts and the scenarios have been adapted to reflect the feedback received from the experts.

The industry scenarios were then used to evaluate the potential European socio-economic impacts of each application. The results of this assessment are presented in Section 8.6.

8.5.1 Approach to describing the scenarios

For each application and scenario a snapshot of what the application-specific industry might look like in the 2020s and by 2030 is captured. This snapshot shows the location of system assembly focussing on the three key global regions of Europe, North America and Asia (primarily China, Japan and S. Korea). The snapshot also indicates what trade flows – in components, systems or both – would be expected at that time, in that scenario, for that specific application. The snapshots are accompanied by a bullet point description of key aspects and drivers of the industry for that application in that scenario in that timeframe. The snapshots focus on illustrating the situation of the relevant European industry so some flows, e.g., to N. America may have been omitted for clarity.

An example snapshot diagram along with a key is shown in Figure 79. This example shows system assembly occurring in Asia (Japan) with flows of components from Europe and N. America to Asia and a flow of systems from Asia to Europe.

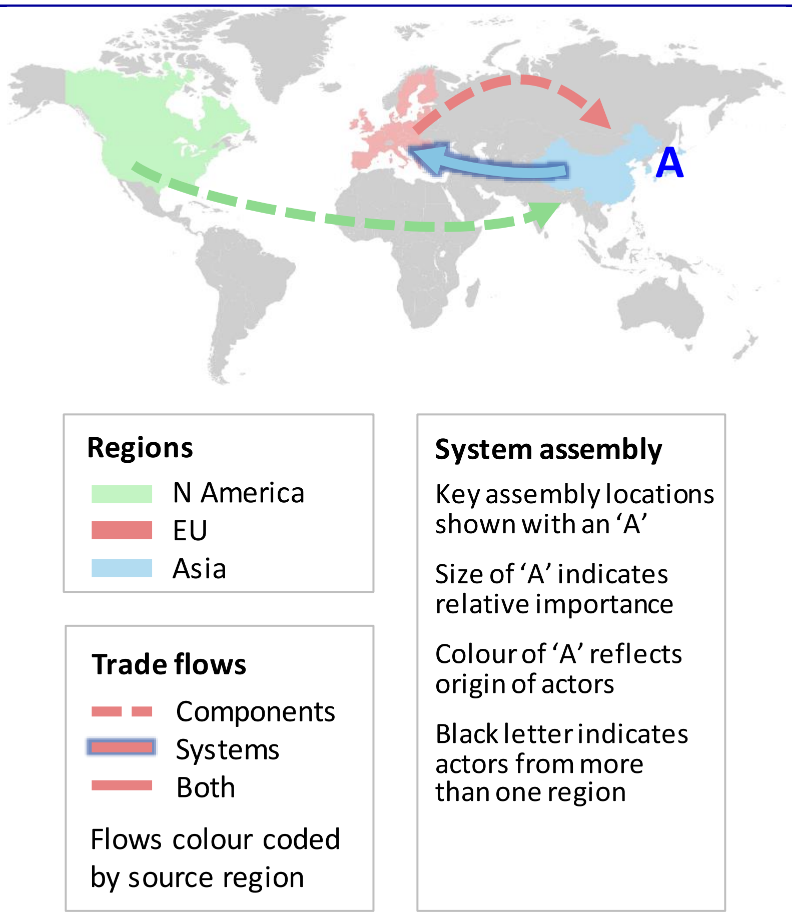
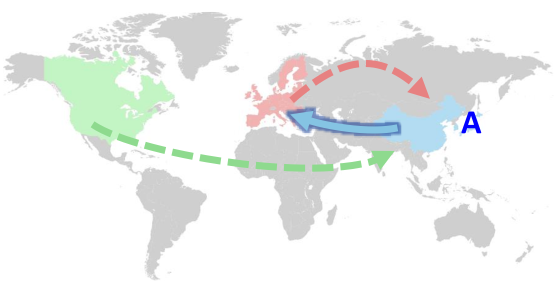


Figure 79: Example industry scenario snapshot diagram with key

8.5.2 FCEV industry scenarios

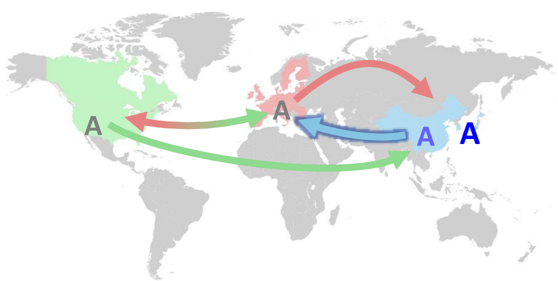
- Automotive OEMs are global actors and rely on a highly optimized global supply chain in which Tier 1 suppliers play a key role
- OEM production processes accommodate both low volume (1,000s to 10,000s per year) and mass market (100,000s per year) models
- OEMs ship vehicles internationally as well as putting in place local assembly capacity in other regions
- For higher volume lines, suppliers will put in place local production capacity to support the assembly plant

Scenario A: 2020s



- Asian OEMs dominate
- Initial supply chain is global using available suppliers

Scenario A: By 2030

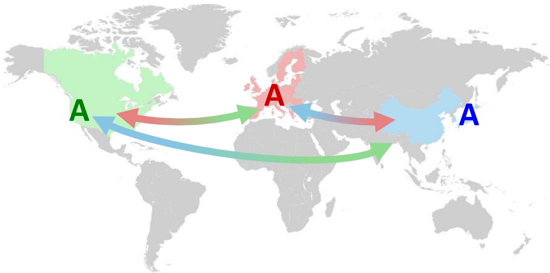


- Asian OEMs are starting to build manufacturing capacity in other regions
- EU and NA OEMs are still in early stages of developing capacity

- Some EU actors export components to Asian OEMs
- Vehicles are imported from Asian OEMs

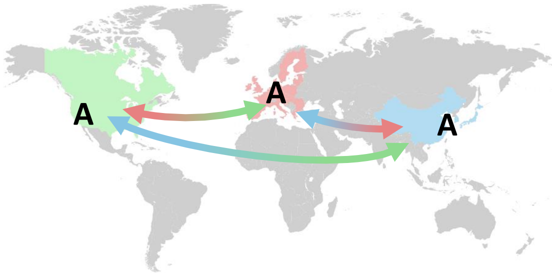
- Regional supply chains in EU and N America are being put in place
- EU actors supply components primarily to local production but also to other regions

Scenario C: 2020s



- EU, Asian and NA OEMs all play a role
- Initial supply chain is global using available suppliers
- EU actors export and import components
- Vehicles are imported and exported

Scenario C: By 2030

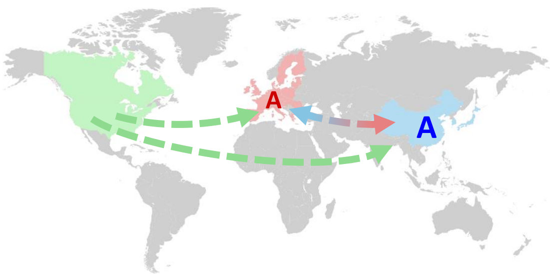


- Supply chain is starting to consolidate around Tier 1s rather than pure FC players
- Proportion of locally produced content increases
- Component suppliers (EU and global) build manufacturing capacity close to vehicle assembly
- EU actors export and import components
- Higher volume models are trending towards local assembly by global OEMs with locally produced parts from global suppliers

8.5.3 FC bus industry scenarios

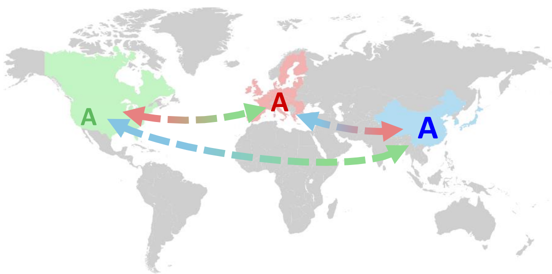
- City bus sector is historically fairly fragmented with small integrators supplying local markets
- Though the stacks are larger and have different requirements, FC buses will benefit from maturation of the PEMFC supply chain promoted by development of other PEMFC transport applications like the FC passenger car segment

Scenario A: 2020s



- Strongest deployment is in China
- Some deployment in EU
- Local integrators in China and EU
- Mixed local and global supply chain
- Stacks are sourced from N America and EU

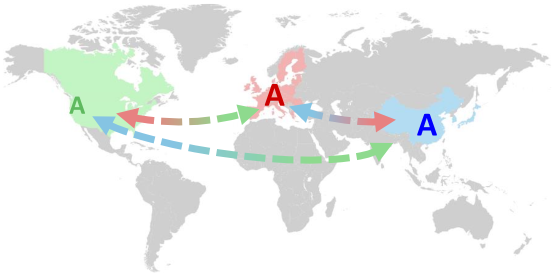
Scenario A: By 2030



- EU component manufacturers supply integrators in other regions
- EU integrators import components from global suppliers

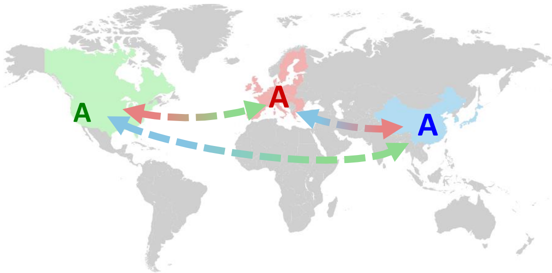
- EU bus stack manufacturers primarily serve the EU bus market
- Some deployment in N America using globally supplied components

Scenario C: 2020s



- Strong development in China and EU
- Some deployment in N America
- Local integrators in each region
- Mixture of global and local supply chain

Scenario C: By 2030

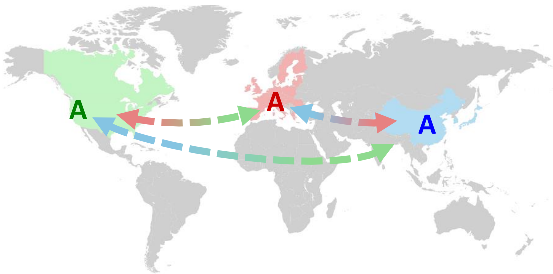


- EU component manufacturers supply integrators in other regions
- EU integrators import components from global suppliers
- EU bus stack manufacturers have a strong share of the EU bus market and are exporting stacks and subsystems

8.5.4 HGV industry scenarios

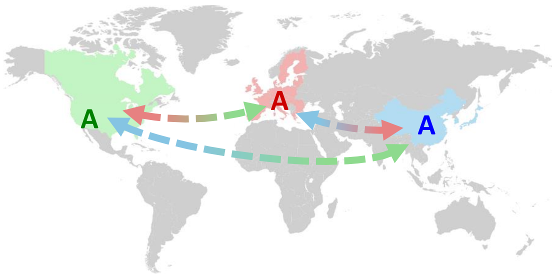
- Application covers trucks >3.5t
- Like passenger cars, HGV manufacturing is dominated by a few large actors with fairly integrated supply chains
- However, volumes are significantly lower than auto OEMs so supply chain is not as heavily optimised
- Though the stacks are larger and have different requirements, FC HGVs will benefit from maturation of the PEMFC supply chain promoted by development of other PEMFC transport applications like the FC passenger car segment

Scenario A: 2020s



- A few OEMs in EU, Asia and N America
- Global supply chain based on available suppliers
- Stacks primarily sourced from established players outside EU

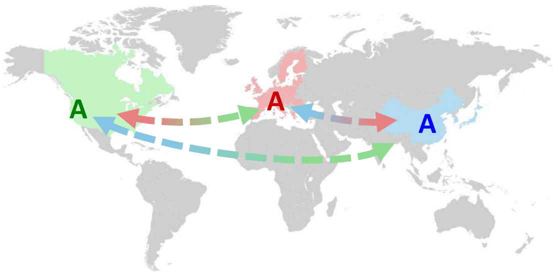
Scenario A: By 2030



- EU component manufacturers supply integrators in other regions
- EU integrators import components from global suppliers
- EU stack manufacturers' share of the EU market is increasing

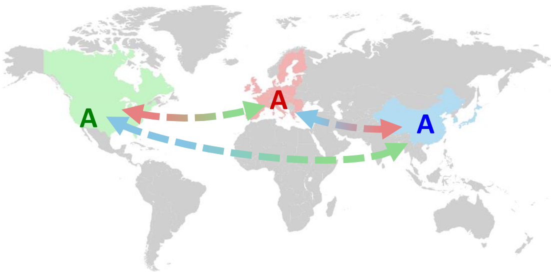
- EU stack manufacturers serve a share of the EU market

Scenario C: 2020s



- OEMs in EU, Asia and N America
- Global supply chain based on available suppliers
- Stacks sourced from established players outside and increasingly within the EU, as the EU technology matures

Scenario C: By 2030

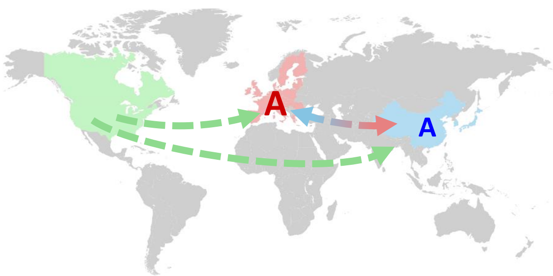


- Supply chains are starting to consolidate around Tier 1s
- Global suppliers developing capacity where assembly occurs
- EU stack manufacturers serve a significant share of the EU market and also serve other regions

8.5.5 Trains and light rail industry scenarios

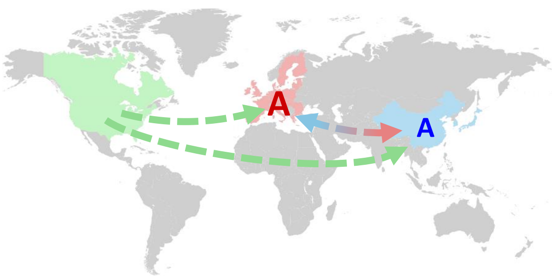
- Trains expected to be dominated by self-propelled carriages – so called multiple units (MU)
- FC trains can be
  - An approach to decarbonise and/or reduce emissions of non-electrified rail segments by replacing diesel units
  - An alternative to deploying light rail with different infrastructure requirements
    1. Overhead lines are costly and may require supporting electricity grid infrastructure
    2. H_2 supply can be localized at depots potentially reducing overall infrastructure cost

Scenario A: 2020s



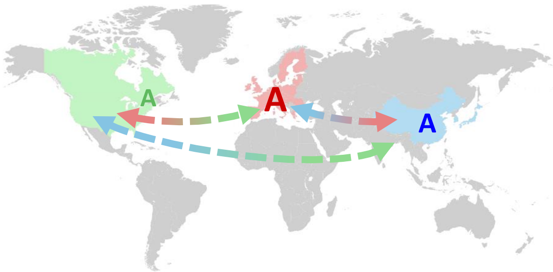
- Major deployment is in EU with some activity in China
- Integrators in EU and China
- Global supply chain based on available suppliers
- Stacks are primarily sourced outside EU

Scenario A: By 2030



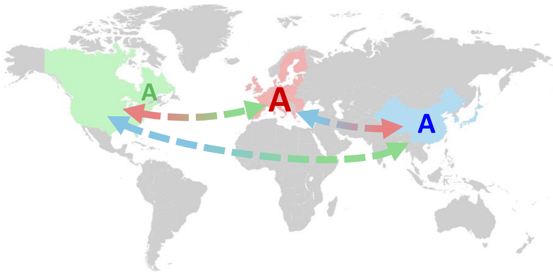
- EU component manufacturers supply integrators in EU and China
- EU integrators import some components
- EU stack manufacturers are starting to play a role, building on experience with HGVs

Scenario C: 2020s



- Strong activity in EU and China, some activity in Canada
- Main integrators in EU and China
- Global supply chain based on available suppliers
- Stacks are primarily sourced outside EU

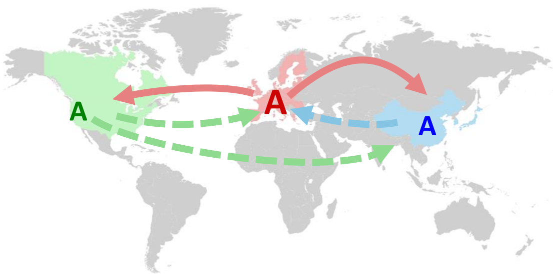
Scenario C: By 2030



- EU component manufacturers supply integrators in EU and China
- EU integrators import other components
- Benefitting from experience in FCEV / bus / HGV segments, supply chains are starting to mature
- EU stack manufacturers supply a share of the EU and global market

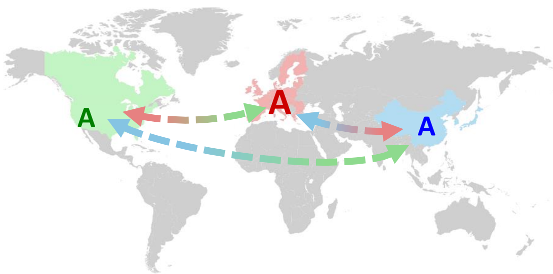
8.5.6 HRS industry scenarios

Scenario A: 2020s



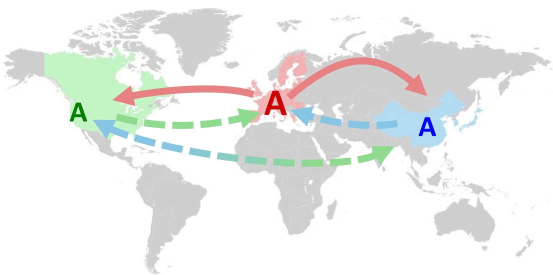
- Deployment principally in California and Asia and some in EU
- EU takes leading supplier role given strength in HRS integration and electrolysis
- Mix of local and global supply chain
- EU actors export systems, subsystems and components

Scenario A: By 2030

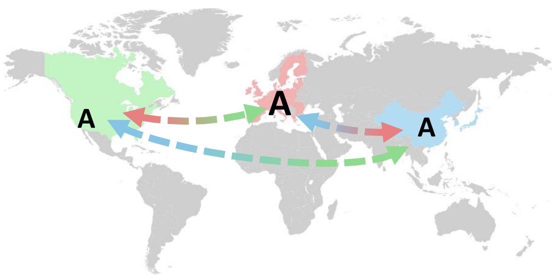


- Integration takes place locally in each key region
- Exports shift down to predominantly subsystems and components

Scenario C: 2020s



Scenario C: By 2030



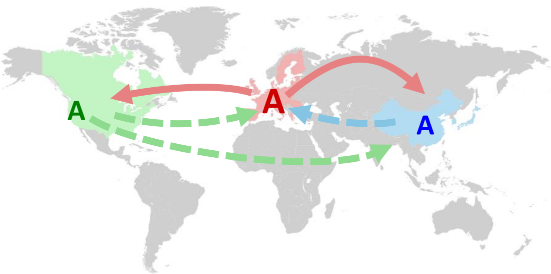
- Deployment in EU, Asia and N America
- EU takes leading supplier role given strength in HRS integration and electrolysis
- Mix of local and global supply chain
- EU actors export systems, subsystems and components

- Exports shift down to predominantly subsystems and components
- Strong system integrators in each region, some as joint ventures with EU actors
- EU and Asian actors have local system/subsystem integration capacity in each key market

8.5.7 Electrolyser industry scenarios

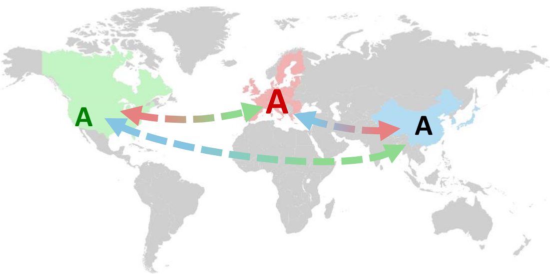
- Electrolysers can be used to
  - Provide potentially green H_2 for vehicle refuelling, refineries and industry
  - Support the integration of greater proportions of variable renewables into the grid
- Refinery and industrial applications – if they take off – could dominate the capacity deployment
- Units in refuelling stations will be lower capacity than industrial ones but will potentially be deployed in greater numbers

Scenario A: 2020s



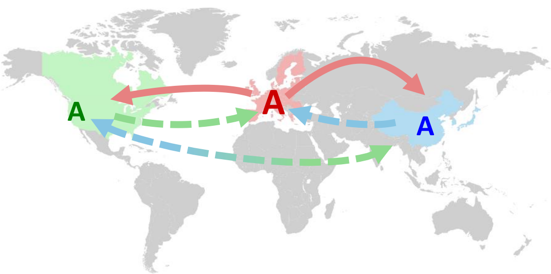
- Electrolyser *capacity* is mostly deployed for green H_2 demonstrations although more *units* are deployed in vehicle refuelling
- Electrolyser role in grid integration is small
- EU integrators play a central role and export electrolysers
- Global supply chain for components

Scenario A: By 2030



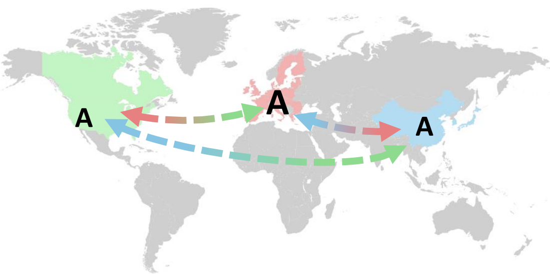
- Integrators have added some system production capacity in Asia to serve the rapidly growing FCEV market and to comply with 'local manufacturing' requirements

Scenario C: 2020s



- Electrolysers deployed for green H_2 in refineries / industry, vehicle refuelling and grid integration

Scenario C: By 2030



- Supply chains are being optimised with more local production in each region
- Imports and exports of components, with systems usually assembled locally

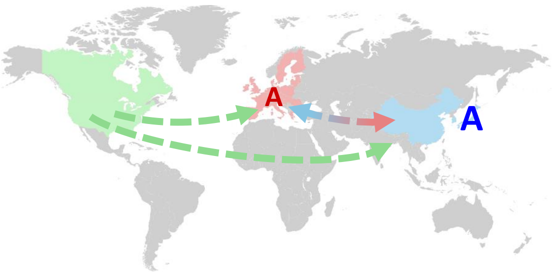
- EU integrators play a central role and export electrolysers
- Some Asian integrators locate final assembly in Europe
- Global supply chain

- EU integrators still lead and dominate EU market, but integrators from all regions serve all markets

8.5.8 Micro CHP industry scenarios

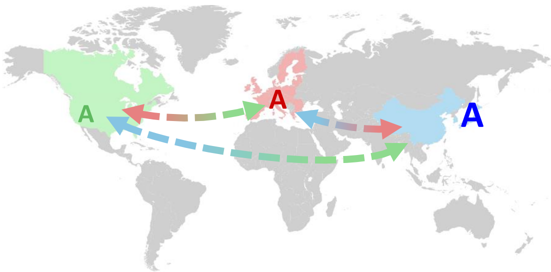
- Small CHP units for residential use (< 5kWe)
- Units expected to operate on natural gas with built in reformers
- SOFC and PEMFC chemistries are expected to be deployed
- Existing channels to client base mean micro-CHP will most likely be deployed by heating equipment manufacturers and/or utilities

Scenario A: 2020s



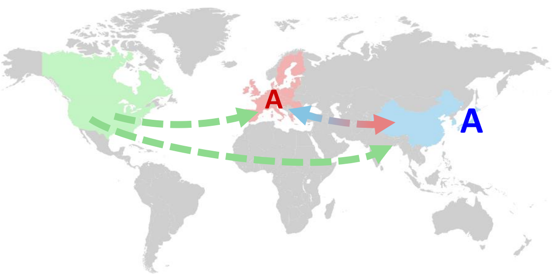
- Deployment remains concentrated in Japan
- Some EU deployment
- Supply chain is focused on Japanese market
- EU component manufacturers export specialized components to Japanese market

Scenario A: By 2030



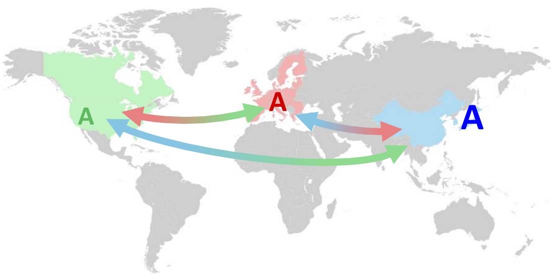
- Japanese market still dominates
- EU system integrators more active, but mostly selling within EU, some activity in N America
- Some EU system integrators import stacks and reformers

Scenario C: 2020s



- Strong deployment in Japan, South Korea and EU
- Integrators primarily supplying their local markets
- Global component supply chain with local integrators
- EU component manufacturers export to integrators in other regions

Scenario C: By 2030

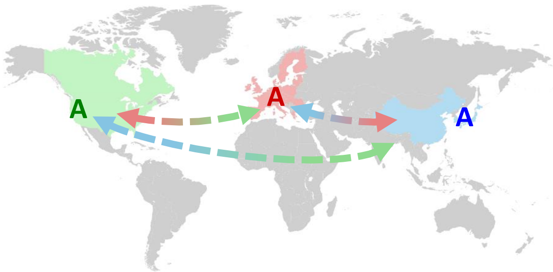


- EU component manufacturers export to integrators in other regions
- EU stack manufacturers supply EU market and export to system integrators in other regions
- EU system integrators export systems to other regions but also import stacks and components

8.5.9 Commercial CHP industry scenarios

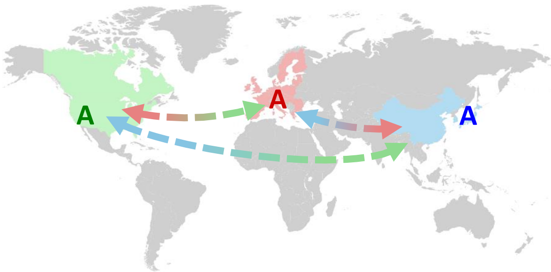
- CHP units for commercial / industrial use (5-100kWe)
- Units expected to operate on natural gas or biogas
- Application expected to be dominated by SOFC chemistry

Scenario A: 2020s



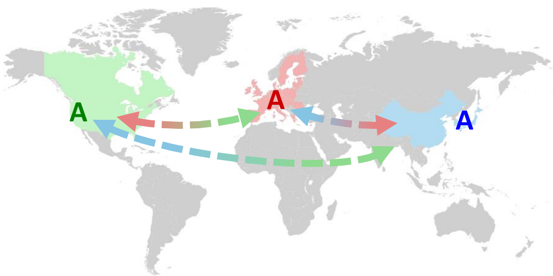
- Moderate deployment in Asia, EU and N America
- Local system integrators – heating equipment suppliers – supply local markets
- SOFC supply chain more vertically integrated than other chemistries so supplier ecosystem is smaller
- Global supply chain

Scenario A: By 2030



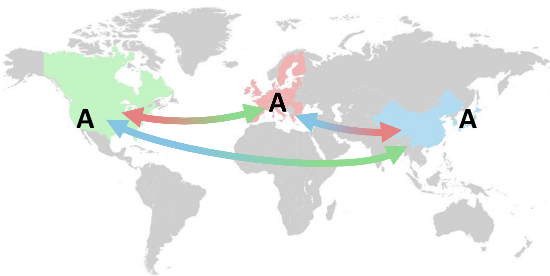
- Market grows but structure remains largely the same – though some specialist suppliers start to emerge
- EU component manufacturers export to system integrators in all regions

Scenario C: 2020s



- Strong deployment in Asia, EU and N America
- Local system integrators primarily supplying local markets
- Supply chain is global and somewhat vertically integrated by manufacturer though specialists are emerging

Scenario C: By 2030



- EU component manufacturers export to system integrators in all regions
- Stronger system integrators export to more than one region and develop local assembly capacity

8.6 Socio-economic impacts

This section provides an overview of socio-economic impacts that can be expected to be related to the European industry performance as sketched out in the two scenarios A and C as described in Section 8.5 above. The analysis takes as a starting point the global and European market scenarios as presented in

Section 8.3 and is based on the assumptions already described in Section 8.4. The main socio-economic impacts of the key applications are highlighted below. The value-added and socio-economic impact figures reported in this section relate to FCH manufacturing and its immediate ecosystem of suppliers. The impact estimates take into consideration the following elements (see Section 8.1 on Value chain definition):

- **Direct jobs**: The labour contributions to value-added at each level of the supply chain covered by the cost breakdown were translated into an estimate of direct jobs associated with those manufacturing activities. The supply chain covered by the cost breakdowns only extends upstream as far as components and processed materials and does not cover the extraction of raw materials.
- **Indirect jobs**: The cost breakdown of each component includes the cost of materials added in that production step. As the supply of these materials is separate from the upstream components explicitly listed in the cost breakdowns, the jobs created in the supply of these materials are estimated as 'indirect' jobs. For the transport applications considered, this included jobs in the supply of the non-FCH elements of the application, namely the rest of the vehicle. Although these jobs are listed as 'indirect', they are still manufacturing jobs that are needed to supply components and materials that go into the FCH applications. **This is different and much narrower than the typical usage of an indirect employment multiplier to capture broad vertical and horizontal extensions to the value chain** (e.g., demand for services generated by manufacturing employees). The numbers in this category will therefore be smaller than for studies with a broad indirect employment definition.
- **Maintenance**: Jobs in maintaining the deployed FCH units are captured separately. This is the only downstream extension included in the analysis.

It is important to note that the socio-economic impact assessment is focused on manufacturing and does not include other extensions such as:

- 'Horizontal' extensions, e.g. the provision of hydrogen for transport applications, the revenues generated by operating the FCH equipment, or the provision of other services related to the FCH applications.
- 'Vertical' extensions, e.g. other supporting business functions: administration, logistics, finance, marketing and sales etc. that are often captured in indirect employment estimates.

The included scope is shown graphically in Figure 80 below. Figure 81 shows how employment in manufacturing in the supply chain is classified as direct and indirect.

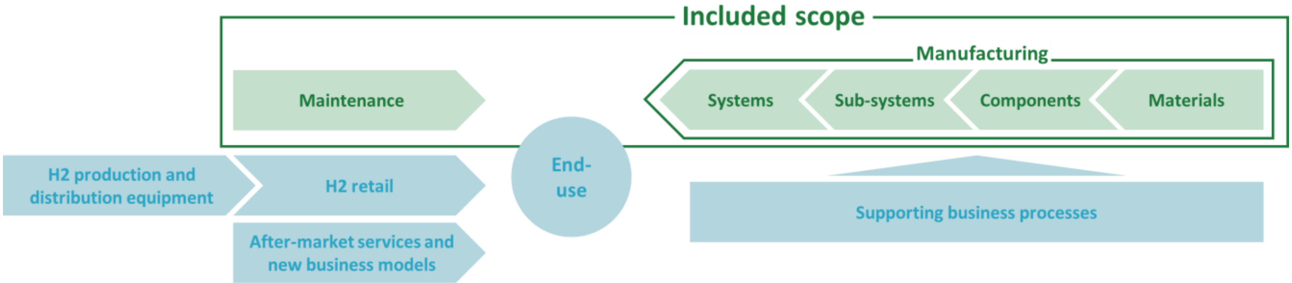


Figure 80: Value chain schematic showing scope included in socio-economic impact assessment

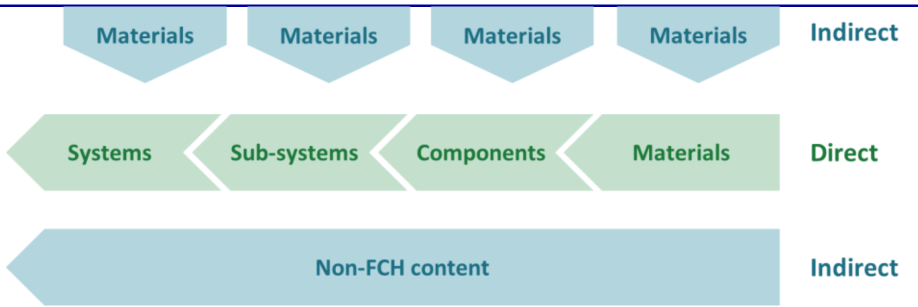


Figure 81: Classification of direct and indirect employment in FCH manufacturing in the analysis

8.6.1 FCEVs

Table 108: Key socio-economic figures for FCEVs by industry scenario (2024 and 2030)

Year	2024			2030		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
Global Market						
System unit cost	€ 10,800	€ 6,800	€ 6,800	€ 8,100	€ 5,400	€ 5,400
Global annual deployment	100,000	650,000	650,000	300,000	1,800,000	1,800,000
Global system production value (million)	€ 1,000	€ 4,400	€ 4,400	€ 2,500	€ 9,800	€ 9,800
Global system O&M value (million)	€ 70	€ 250	€ 250	€ 260	€ 1,090	€ 1,090
European market and production						
European annual deployment (units)	20,000	170,000	170,000	60,000	470,000	470,000
European production value (million)	€ 100	€ 600	€ 1,400	€ 300	€ 1,800	€ 3,100
European O&M value (million)	€ 10	€ 70	€ 70	€ 50	€ 290	€ 290
Macro-economic impact						
Value added - Total (million)	€ 30	€ 170	€ 400	€ 80	€ 450	€ 760
Value added - Labour (million)	€ 10	€ 40	€ 90	€ 20	€ 120	€ 190
Value added - Capital (million)	€ 10	€ 80	€ 200	€ 30	€ 200	€ 340
Value added - Margin (million)	€ 10	€ 50	€ 110	€ 20	€ 140	€ 230
European annual trade balance impact (million)	-€ 100	-€ 600	€ 200	-€ 100	-€ 800	€ 500
Employment impact						
Direct employment system production (fte)	200	1,000	2,400	500	3,100	5,100
Direct employment O&M (fte)	100	600	600	400	2,400	2,400
Indirect employment (fte)	800	6,700	16,100	3,200	25,400	43,600
Sum (fte)	1,100	8,300	19,100	4,100	30,900	51,100

Industry scenario A: Low deployment, low EU Production share

- *Direct employment* – With an annual global production volume of 300 thousand units, only 39,000 passenger cars and light commercial vehicles (13%) are expected to be produced in Europe. The total European Production value of fuel-cell related parts is therefore limited in this scenario, as the European share in an already low global market scenario is limited and as European production is below that. The production value of FC systems amounts to €300m per year [166], with a corresponding value-added of about €80m[167]. Most value-added would come from subsystem and (sub-)component production and much less so from system integration. Overall European number of employees on the production line related to these activities would be minimal – on the order of 500.

[166] The total estimated value of FC systems per car is € 8,114
[167] The value-added by component has been described in section 7.4.

- *Maintenance* – Maintenance would be expected to amount to €50m annually [168] due to the already installed capacity built up in the years prior to 2030, employing a further 400. Other horizontal extensions are not included[169].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 700 staff. As FC systems would only make up a share (expected is 27%) of the vehicles' value, the total non-fuel cell related production value would be expected to be around €800m, engaging a further 2,500 employees[170].
- *Trade balance* – As the European demand in this scenario would be rather weak, the case for (Asian) OEMs to build production capacity in Europe would be rather weak too. Whilst European exports would be meaningful for a number of components (as mentioned above), overall trade balance for Europe would be negative, on the order of €100m. This would be due mostly to the fact that OEM assembly would still, to a large extent take place outside of Europe (demonstrated by the fact that the total number of units sold in the European market would be 60,000, whilst the European production would be only 39,000 units).
- In conclusion, the overall value-added and employment related to the production of FC systems would be low in this scenario. Several multipliers would make the overall socio-economic impact more substantial. It would however be doubtful – with European value chains being rather fragmented whether the European production basis in this scenario would be sufficiently strong to withstand and/or substantially expand in the subsequent period – in light of global competition and weak European market development.

Industry scenario C: High deployment, High EU production share

- *Direct employment* – This is a radically different scenario, not only because global production volume of 1.8m units, but also due to the fact that over 30% of these passenger cars and light commercial vehicles (570,000) are expected to be produced in Europe. The expected production value of European-produced FC systems amounts to €3.1 bn per year[171], with a corresponding value-added of about €760m[172]. Overall, the European number of direct employees on the production line related to these activities would be around 5,100.
- *Maintenance* – Maintenance would be expected to amount to €290m annually[173] due to the already installed capacity built up in the years prior to 2030, employing a further 2,400. Other horizontal extensions are not included[174].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 7,000 staff. FC systems would only make up a small share (expected is 20%) of the vehicles, due to the fact that economies of scale would apply only

[168] Assuming maintenance to be 2% of capital costs. Assumption based on https://www.leaseplan.com/corporate/news-and-media/newsroom/2018/car%20cost%20index; and https://elib.dlr.de/75697/1/EVS26_Propfe_final.pdf

[169] This ratio between production and non-production workers is typically 1:4 in mature automobile manufacturing; however due to the relative low production volumes in this scenario and the less mature nature of FCEV production by 2030, a more conservative 1: 3 ratio could be applied. This would amount to another 1,500 jobs, which are not included in the above table.

[170] It is assumed that the non-FC system part (the 'glider' i.e., vehicle without a drive train) estimate amounts to €21,648 (based on information from the ICCT and TMU.

[171] The total estimated value of FC systems per car is € 5.500, lower than in Scenario A due to economies of scale.

[172] The value-added by component has been described in section 7.4.

[173] Assuming maintenance to be 2% of capital costs. Assumption based on https://www.leaseplan.com/corporate/news-and-media/newsroom/2018/car%20cost%20index; and https://elib.dlr.de/75697/1/EVS26_Propfe_final.pdf

[174] This ratio between production and non-production workers is typically 1:4 in mature automobile manufacturing; however due to the relative low production volumes in this scenario and the less mature nature of FCEV production by 2030, a more conservative 1:3 ratio could be applied. This would amount to another 15,300 jobs, which are not included in the above table.

to the FC system part and not to the remainder of the vehicle. Hence, the total non-fuel cell related production value would be expected to be over €12 bn, engaging a further 37,000 employees.[175, 176]

- *Trade balance* – As the European production in this scenario would be much stronger, the supply chain is starting to consolidate around Tier 1s rather than pure FC players. The proportion of locally produced content increases, whilst component suppliers (European and global) build manufacturing capacity close to vehicle assembly. European actors export and import components, but the overall trade balance for Europe is positive – amounting to about €500m. This can be illustrated by the fact that the overall amount of vehicles produced in Europe (570,000) is expected to be higher than European demand (470,000), thus allowing for exports of 100,000 units.
- In conclusion, the overall value-added and employment related to the production of FC systems would be entirely different in this scenario. Whilst direct value-added and employment at FC system production lines would only be modest, several multipliers would make the overall socio-economic impact substantial. European value chains being much more developed, Europe's competitive position would be much more advantageous vis-à-vis other global players – offering substantial room for expansion in the period after as well.

8.6.2 Fuel cell buses

Table 109: Key socio-economic figures for fuel cell buses by industry scenario (2024 and 2030)

Year	2024			2030		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
Global Market						
System unit cost	€ 59,400	€ 46,600	€ 46,600	€ 46,900	€ 34,900	€ 34,900
Global annual deployment	4,000	10,000	10,000	10,000	40,000	40,000
Global system production value (million)	€ 240	€ 470	€ 470	€ 470	€ 1,400	€ 1,400
Global system O&M value (million)	€ 20	€ 40	€ 40	€ 60	€ 150	€ 150
European market and production						
European annual deployment (units)	200	1,000	1,000	600	3,800	3,800
European production value (million)	€ 10	€ 40	€ 50	€ 20	€ 110	€ 160
European O&M value (million)	€ 1	€ 3	€ 3	€ 3	€ 12	€ 12
Macro-economic impact						
Value added - Total (million)	€ 3	€ 8	€ 13	€ 5	€ 22	€ 33
Value added - Labour (million)	€ 1	€ 2	€ 3	€ 1	€ 6	€ 8
Value added - Capital (million)	€ 2	€ 4	€ 6	€ 3	€ 9	€ 14
Value added - Margin (million)	€ 1	€ 3	€ 4	€ 2	€ 7	€ 11
European annual trade balance impact (million)	€ -3	€ 0	€ 0	€ -6	€ 0	€ 0
Employment impact						
Direct employment system production (fte)	20	50	70	30	150	220
Direct employment O&M (fte)	10	30	30	30	100	100
Indirect employment (fte)	110	380	570	260	1,450	2,170
Sum (fte)	140	460	670	320	1,700	2,490

Industry scenario A: Low deployment, low EU Production share

[175] It is assumed that the non-FC system part (the 'glider' i.e., vehicle without a drive train) estimate amounts to €21,648 (based on information from the ICCT and TMU) – hence similar to Scenario A, as economies of scale are expected to apply only to the FC-system.
[176] It can be observed that the overall cost price difference for FCEV's as a whole amounts to only 10% between the scenarios A and C. It is therefore expected that differences in demand are mostly exogenous, e.g. through the policy framework.

- *Direct employment* – With an annual global production volume of 10,000 thousand, only 600 are expected to be deployed in Europe and only 470 produced. The total European production value of fuel cell-related parts is therefore limited in this scenario – €20m per year, with a corresponding value-added of about €5m. Overall, the European number of employees on the production line related to these activities would be around 30.
- *Maintenance* – Maintenance would be expected to amount to €3m annually[177] due to the already installed capacity built up in the years prior to 2030, employing a further 30. Other horizontal extensions are not included[178].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 50 staff. As FC systems would only make up a share (expected is 24%) of the vehicles' value, the total non-fuel cell related production value would be expected to be around €70m[179], engaging a further 210 employees.
- *Trade balance* – European demand in this scenario would be weak, and the case for local system integration not strong. European component manufacturers would export some, notably to North America but overall OEMs to build production capacity in Europe would be rather weak too. Whilst European exports would be meaningful for a number of components (as mentioned above), overall trade balance for Europe would be negative (net imports of €6m).
- In conclusion, the overall value-added and employment related to the production of FC buses systems would be very low in this scenario. Several multipliers would make the overall socio-economic impact somewhat more meaningful.

Industry scenario C: High deployment, High EU production share

- *Direct employment* – Global as well as European deployment are more substantial in this scenario, and on balance the European demand for 4,000 buses annually would be similar to European production levels. The expected production value of European-produced FC buses amounts to €160m per year, with a corresponding value-added of about €33m. Overall, the European number of employees on the production line related to these activities would be around 220.
- *Maintenance* – Maintenance would be expected to amount to €12.4m annually – due to the already installed capacity built up in the years prior to 2030, employing a further 100. Other horizontal extensions are not included[180].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 380 staff. As FC systems would only make up a share (expected is 21%) of the vehicles' value, the total non-fuel cell related production value would be expected to be around €600m, engaging a further 1,800 employees.
- *Trade balance* – Overall, European trade balance would be zero, however this would mask the fact that European bus stack manufacturers have a strong share of the European bus market and are exporting stacks and subsystems.

[177] Assuming maintenance to be 2% of capital costs. Given the intensive use of FC buses this estimate is likely to be conservative.
[178] This ratio between production and non-production workers is typically 1:4 in mature automobile manufacturing; however due to the relative low production volumes in this scenario and the less mature nature of FCEB production by 2030, a more conservative 1:3 ratio could be applied. This would amount to another 90 jobs, which are not included in the above table.
[179] Across the scenarios, the total estimated value of non-FC systems parts per bus is estimated at a constant € 150.000
[180] This ratio between production and non-production workers is typically 1:4 in mature automobile manufacturing; however due to the relative low production volumes in this scenario and the less mature nature of FCEB production by 2030, a more conservative 1:3 ratio could be applied. This would amount to another 660 jobs, which are not included in the above table.

- In conclusion, although the overall value-added and employment related to the production of FC bus systems would be modest in this scenario, several multipliers would make the overall socio-economic impact of this segment meaningful.

8.6.3 HGVs (trucks)

Table 110: Key socio-economic figures for HGVs (trucks) by industry scenario (2024 and 2030)

Year	2024			2030		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
Global Market						
System unit cost	€ 70,600	€ 54,400	€ 54,400	€ 54,700	€ 40,000	€ 40,000
Global annual deployment	1,000	4,000	4,000	4,000	17,000	17,000
Global system production value (million)	€ 80	€ 230	€ 230	€ 240	€ 680	€ 680
Global system O&M value (million)	€ 0	€ 10	€ 10	€ 20	€ 70	€ 70
European market and production						
European annual deployment (units)	200	1,000	1,000	600	4,000	4,000
European production value (million)	€ 10	€ 40	€ 70	€ 30	€ 130	€ 220
European O&M value (million)	€ 1	€ 3	€ 3	€ 3	€ 15	€ 15
Macro-economic impact						
Value added - Total (million)	€ 3	€ 12	€ 18	€ 7	€ 30	€ 52
Value added - Labour (million)	€ 0	€ 2	€ 4	€ 1	€ 7	€ 12
Value added - Capital (million)	€ 2	€ 6	€ 10	€ 4	€ 14	€ 24
Value added - Margin (million)	€ 1	€ 3	€ 5	€ 2	€ 9	€ 16
European annual trade balance impact (million)	€ -2	€ 0	€ 0	€ -7	€ 0	€ 0
Employment impact						
Direct employment system production (fte)	10	60	100	40	180	320
Direct employment O&M (fte)	10	20	20	30	130	130
Indirect employment (fte)	100	520	810	360	1,980	3,330
Sum (fte)	120	600	930	430	2,290	3,780

Industry scenario A: Low deployment, low EU Production share

- *Direct employment* – The market for HGVs is limited in this scenario, and unit numbers are somewhat below those for FCEBs. With an annual global production volume of 4,000 thousand, only 600 are expected to be deployed in Europe and only 500 of those produced in Europe. However, due to the need for high-powered vehicles and the larger size and/or number of stacks, the FC-related system costs are expected to be substantial (€54,700 per unit), resulting in a total European production value of fuel-cell related parts of €30m per year, with a corresponding value-added of about €7m – comparable to that of buses. Overall European number of employees on the production line related to these activities would be around 40.
- *Maintenance* – Maintenance would be expected to amount to €3m annually[181] due to the already installed capacity built up in the years prior to 2030, employing a further 30. Other horizontal extensions are not included[182].

[181] Assuming maintenance to be 2% of capital costs. Given the intensive use of HGVs this estimate is likely to be conservative.
[182] This ratio between production and non-production workers is typically 1:4 in mature automobile manufacturing; however due to the relative low production volumes in this scenario and the less mature nature of FC HGV production by 2030, a more conservative 1:3 ratio could be applied. This would amount to another 120 jobs, which are not included in the above table.

- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 60 staff. As FC systems would only make up a share (expected is 26%) of the vehicles' value, the total non-fuel cell related production value would be expected to be around €100m[183], engaging a further 300 employees.
- *Trade balance* – Imports and exports of components mostly, however the overall trade balance for Europe would be negative (net imports of €7m).
- In conclusion, the overall value-added and employment related to the production of HGV systems would be very low in this scenario. Several multipliers would make the overall socio-economic impact somewhat more meaningful.

Industry scenario C: High deployment, High EU production share

- *Direct employment* – Annual global production volume of 17,000 thousand, of which 4,000 deployed in Europe, allows more room for production in Europe – about 5,000 are produced in Europe by 2030. Economies of scale start to kick in (FC-related system costs are expected to come down to €40,000 per unit), resulting in a total European production value of fuel-cell related parts of €220m per year, with a corresponding value-added of about €52m. Overall European number of employees on the production line related to these activities would be around 320.
- *Maintenance* – Maintenance would be expected to amount to €15m annually – due to the already installed capacity built up in the years prior to 2030, employing a further 130. Other horizontal extensions are not included[184].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 500 staff. As FC systems would only make up a share (expected is 21%) of the vehicles' value, the total non-fuel cell related production value would be expected to be around €950m[185], engaging a further 2,800 employees.
- *Trade balance* – Imports and exports of components, with a neutral trade balance as a result.
- In conclusion, the overall value-added and employment related to the production of HGV systems would be moderate in this scenario. Several multipliers would make the overall socio-economic impact related to the production of HGVs meaningful.

[183] Assuming the non-FC part of the HGV is € 200,000 per unit
[184] This ratio between production and non-production workers is typically 1:4 in mature automobile manufacturing; however due to the relative low production volumes in this scenario and the less mature nature of FC HGV production by 2030, a more conservative 1:3 ratio could be applied. This would amount to another 960 jobs, which are not included in the above table.
[185] Assuming the non-FC part of the HGV is € 200,000 per unit

8.6.4 FC systems for trains and lightrail

Table 111: Key socio-economic figures for FC systems for trains and lightrail by industry scenario (2024 and 2030)

Year	2024			2030		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
Global Market						
System unit cost	€ 206,100	€ 167,100	€ 167,100	€ 167,600	€ 128,900	€ 128,900
Global annual deployment	30	160	160	80	400	400
Global system production value (million)	€ 10	€ 30	€ 30	€ 10	€ 50	€ 50
Global system O&M value (million)	€ 0	€ 0	€ 0	€ 0	€ 10	€ 10
European market and production						
European annual deployment (units)	10	70	70	20	160	160
European production value (million)	€ 1	€ 9	€ 12	€ 3	€ 17	€ 23
European O&M value (million)	€ 0	€ 1	€ 1	€ 0	€ 3	€ 3
Macro-economic impact						
Value added - Total (million)	€ 0	€ 2	€ 2	€ 1	€ 3	€ 4
Value added - Labour (million)	€ 0	€ 0	€ 1	€ 0	€ 1	€ 1
Value added - Capital (million)	€ 0	€ 1	€ 1	€ 0	€ 1	€ 1
Value added - Margin (million)	€ 0	€ 1	€ 1	€ 0	€ 1	€ 1
European annual trade balance impact (million)	€ 0	€ 0	€ 0	€ -1	€ 0	€ 0
Employment impact						
Direct employment system production (fte)	-	10	20	-	20	30
Direct employment O&M (fte)	-	10	10	-	20	20
Indirect employment (fte)	50	420	580	150	1,020	1,400
Sum (fte)	50	440	610	150	1,060	1,450

Industry scenario A: Low deployment, low EU Production share

- *Direct employment* – By 2030, this application is considered only a niche market in this scenario, and global deployment is expected to be only 80 units, however Europe captures a relatively higher share of this (25%). Due to the need for very high-powered systems vehicles and the larger size and/or number of stacks, the FC-related system costs are expected to be substantial (€167,600 per unit), resulting in a total European production value of Fuel-cell related parts of €3m per year, with a corresponding value-added of about €1m. Overall European number of employees on the production line related to these activities would be negligible.
- Indirect socio-economic impacts are considered insufficiently small to report about.

Industry scenario C: High deployment, High EU production share

- *Direct employment* – By 2030, this global deployment is expected to be almost 400 units, of which 40% exercised by Europe. Total European production value of fuel cell-related parts is estimated at €23m per year, with a corresponding value-added of about €4m. Overall European number of employees on the production line related to these activities would be around 30.
- *Indirect employment* – Indirect socio-economic impacts, notably those related to the production of the trains as a whole, could however be much higher, at an estimated 1,400, as the non-fuel-cell related value of trains will be high [186].

[186] The non-FCH-related value of a unit is estimated at € 2.8m.

- In conclusion, it would be important to see FC train systems production together with that of buses and HGVs, and to be aware of the (strategic) importance of the remainder of the non-FCH part of the value chain – especially as conventional train production capacity in Europe is high and as its future competitiveness will be at stake.

8.6.5 HRS industry scenarios

Table 112: Key socio-economic figures for HRS industry scenario (2024 and 2030)

Year	2024			2030		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
Global Market						
System cost - retail station	€ 4,900,000	€ 4,200,000	€ 4,200,000	€ 4,800,000	€ 3,600,000	€ 3,600,000
System cost - bus fleet station	33,700,000	28,900,000	28,900,000	30,100,000	22,400,000	22,400,000
Global annual deployment	€ 200	€ 1,300	€ 1,300	€ 700	€ 3,700	€ 3,700
Global system production value (million)	€ 1,400	€ 6,200	€ 6,200	€ 3,900	€ 15,200	€ 15,200
Global system O&M value (million)	€ 100	€ 360	€ 360	€ 420	€ 1,620	€ 1,620
European market and production						
European annual deployment (units)	€ 40	€ 340	€ 340	€ 110	€ 920	€ 920
European production value (million)	€ 280	€ 1,860	€ 2,010	€ 800	€ 4,590	€ 4,970
European O&M value (million)	€ 20	€ 90	€ 90	€ 70	€ 410	€ 410
Macro-economic impact						
Value added - Total (million)	€ 100	€ 690	€ 800	€ 300	€ 1,720	€ 1,980
Value added - Labour (million)	€ 50	€ 340	€ 390	€ 150	€ 840	€ 960
Value added - Capital (million)	€ 40	€ 250	€ 290	€ 110	€ 610	€ 710
Value added - Margin (million)	€ 20	€ 110	€ 130	€ 50	€ 280	€ 310
European annual trade balance impact (million)	€ 50	€ 310	€ 460	€ 130	€ 760	€ 1,150
Employment impact						
Direct employment system production (fte)	1,300	8,900	10,200	3,800	22,000	25,200
Direct employment O&M (fte)	100	800	800	600	3,400	3,400
Indirect employment (fte)	500	3,500	3,600	1,500	8,500	8,900
Sum (fte)	1,900	13,200	14,600	5,900	33,900	37,500

Industry scenario A: Low deployment, low EU Production share

- *Direct employment* – By 2030, European production value is expected to be around €800m (20% of global system production value). Most of the market would be related to bus fleet stations, rather than retail stations. Corresponding value-added would be about €300m, of which half would be labour. The overall European number of employees related to system production would therefore be high, 3,800.
- *Maintenance* – Maintenance would be expected to amount to €70m annually[187], employing a further 600. Other horizontal extensions are not included[188].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 1,500 staff.

[187] Assuming maintenance to be 2% of capital costs.
[188] A conservative 1:2 ratio between production and non-production workers would result in a further 7,600 staff, which are not included in the above tables.

- *Trade balance* – Overall trade balance would be positive, at a value of about €130 million. Integration may take place locally in each region, however European producers would be well placed to supply subsystems and components globally.

Industry scenario C: High deployment, High EU production share

- *Direct employment* – By 2030, European production value is expected to be a substantial €5 bn, about 1/3 of global production value (€15 bn). Corresponding European value-added would be €2 bn, of which about half is related to labour inputs. The overall European number of employees related to system production would therefore be very high, 25,000.
- *Maintenance* – Maintenance would be expected to amount to €406m annually[189], employing a further 3,500. Other horizontal extensions are not included[190].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 9,000 staff.
- *Trade balance* – Overall trade balance would be substantial and positive, at a value of over €1 billion (€1,150m). Whilst system integration would take place in each region, EU actors could contribute through joint ventures. Exports shift down to predominantly subsystems and components.

8.6.6 Electrolyser industry scenarios

Table 113: Key socio-economic figures for electrolyser industry scenario (2024 and 2030)

Year	2024			2030		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
Global Market						
Global system production value (million)	€ 230	€ 730	€ 730	€ 500	€ 2,000	€ 2,000
Global system O&M value (million)	€ 20	€ 140	€ 140	€ 120	€ 450	€ 450
European market and production						
European production value (million)	€ 91	€ 180	€ 190	€ 190	€ 480	€ 520
European O&M value (million)	€ 6.4	€ 10	€ 10	€ 20	€ 42	€ 42
Macro-economic impact						
Value added - Total (million)	€ 29	€ 58	€ 66	€ 64	€ 160	€ 180
Value added - Labour (million)	€ 10	€ 19	€ 21	€ 21	€ 52	€ 59
Value added - Capital (million)	€ 13	€ 26	€ 30	€ 29	€ 73	€ 84
Value added - Margin (million)	€ 6.6	€ 13	€ 14	€ 14	€ 36	€ 40
European annual trade balance impact (million)	€ 15	€ 29	€ 44	€ 32	€ 81	€ 120
Employment impact						
Direct employment system production (fte)	260	500	560	550	1,400	1,600
Direct employment O&M (fte)	54	85	85	170	360	360
Indirect employment (fte)	180	350	370	390	960	1,000
Sum (fte)	490	940	1,000	1,100	2,700	2,900

Industry scenario A: Low deployment, low EU Production share

- *Direct employment* – By 2030, European production value is expected to be around €190m. Corresponding value-added would be about €64m. The overall European number of employees on the production line related to these activities would be 550.

189 Assuming maintenance to be 2% of capital costs.
190 A conservative 1:2 ratio between production and non-production workers would result in a further 50,000 staff, which are not included in the above tables.

- *Maintenance* – Maintenance would be expected to amount to €20m annually[191], employing a further 170. Other horizontal extensions are not included[192].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 390 staff.
- *Trade balance* – Overall trade would be positive (€32m), reflecting the strong position of European integrators having added some system production capacity in Asia to serve the rapidly growing market.

Industry scenario C: High deployment, High EU production share

- *Direct employment* – By 2030, European production value is expected to be around €520m. Corresponding value-added would be about €180m. Overall European number of employees on the production line related to these activities would be 1,600.
- *Maintenance* – Maintenance would be expected to amount to €42m annually, employing a further 360. Other horizontal extensions are not included[193].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 1,000.
- *Trade balance* – Overall trade would substantial and positive (€120m surplus), as EU integrators still lead and dominate the EU market, supplemented by exports of components.

8.6.7 Micro CHP industry scenarios

It is assumed that by 2030 the split between PEM micro CHP and SOFC will be 40/60% based on deployment numbers in all industry scenarios. However, costs of SOFC micro CHP per unit will be higher than for PEM micro CHP, leading to differentiated socio-economic impacts.

Table 114: Key socio-economic figures for micro CHP industry scenario (2024 and 2030)

Year	2024			2030		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
Global Market						
Global system production value (million)	€ 400	€ 1,300	€ 1,300	€ 1,200	€ 3,600	€ 3,600
Global system O&M value (million)	€ 50	€ 100	€ 100	€ 140	€ 400	€ 400
European market and production						
European production value (million)	€ 25	€ 130	€ 160	€ 74	€ 360	€ 440
European O&M value (million)	€ 3.5	€ 11	€ 11	€ 10	€ 44	€ 44
Macro-economic impact						
Value added - Total (million)	€ 6.1	€ 30	€ 37	€ 17	€ 79	€ 97
Value added - Labour (million)	€ 2.9	€ 15	€ 18	€ 8.4	€ 39	€ 48
Value added - Capital (million)	€ 1.7	€ 7.9	€ 10	€ 4.5	€ 19	€ 23
Value added - Margin (million)	€ 1.5	€ 7.6	€ 9.3	€ 4.3	€ 21	€ 25
European annual trade balance impact (million)	-€ 2.8	-€ 14	€ 14	-€ 8.2	-€ 40	€ 40
Employment impact						
Direct employment system production (fte)	76	390	470	220	1,000	1,300
Direct employment O&M (fte)	17	53	53	45	200	200
Indirect employment (fte)	56	300	360	170	840	1,000
Sum (fte)	150	740	890	440	2,100	2,500

[191] Assuming maintenance to be 2% of capital costs.
[192] A conservative 1:2 ratio between production and non-production workers would result in a further 1,100 staff, which are not included in the above tables.
[193] A conservative 1:2 ratio between production and non-production workers would result in a further 3,200 staff, which are not included in the above tables.

Industry scenario A: Low deployment, low EU Production share

- *Direct employment* – By 2030, European production value is expected to be around €74m (€22m PEM and €52m SOFC). Corresponding value-added would be about €17m (€6m PEM and €11m SOFC). The overall European number of employees on the production line related to these activities would be 220 (70 in PEM and 150 in SOFC).
- *Maintenance* – Maintenance would be expected to amount to €10m annually[194] (mostly in SOFC), employing a further 50. Other horizontal extensions are not included[195].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 170 staff.
- *Trade balance* – Overall trade would be limited, with European system integrators mostly selling within the EU, and importing stacks and reformers (leading to a slightly negative trade balance).

Industry scenario C: High deployment, High EU production share

- *Direct employment* – By 2030, European production value is expected to be around €440m (€120m PEM and €320m SOFC). Corresponding value-added is about €100m (€40m PEM and €60m SOFC). Overall European number of employees on the production line related to these activities would be 1,300 (400 in PEM and 900 in SOFC).
- *Maintenance* – Maintenance would be expected to amount to €44m annually, employing a further 200. Other horizontal extensions are not included[196].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 1,000 (260 in PEM, 770 in SOFC).
- *Trade balance* – Overall trade would be modest but with an export surplus, as European system integrators would export systems to other regions more than they would import stacks and components.

8.6.8 Commercial CHP industry scenarios

It is assumed that by 2030 the split between PEM and SOFC commercial CHP will be 50/50% in all industry scenarios based on deployment numbers. However, system unit costs are expected to be substantially higher for PEM than for SOFC commercial CHP, leading to different socio-economic impacts.

[194] Assuming maintenance to be 2% of capital costs.
[195] A conservative 1:2 ratio between production and non-production workers would result in a further 440 staff, which are not included in the above tables.
[196] A conservative 1:2 ratio between production and non-production workers would result in a further 2,600 staff, which are not included in the above tables.

Table 115: Key socio-economic figures for commercial CHP industry scenario (2024 and 2030)

Year	2024			2030		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
Global Market						
Global system production value (million)	€ 300	€ 1,600	€ 1,600	€ 1,000	€ 5,600	€ 5,600
Global system O&M value (million)	€ 16	€ 76	€ 110	€ 93	€ 530	€ 750
European market and production						
European production value (million)	€ 16	€ 190	€ 320	€ 54	€ 680	€ 1,200
European O&M value (million)	€ 0.9	€ 10	€ 10	€ 5.5	€ 71	€ 71
Macro-economic impact						
Value added - Total (million)	€ 4.5	€ 54	€ 96	€ 15	€ 200	€ 360
Value added - Labour (million)	€ 2.1	€ 26	€ 49	€ 7.5	€ 98	€ 180
Value added - Capital (million)	€ 1.3	€ 14	€ 25	€ 3.9	€ 52	€ 91
Value added - Margin (million)	€ 1.1	€ 13	€ 23.0	€ 3.7	€ 47	€ 85
European annual trade balance impact (million)	-€ 1.8	-€ 21	€ 29	-€ 6.0	-€ 75	€ 110
Employment impact						
Direct employment system production (fte)	56	700	1,300	200	2,600	4,800
Direct employment O&M (fte)	8	86	86	46	600	600
Indirect employment (fte)	34	400	670	120	1,400	2,400
Sum (fte)	98	1,200	2,000	360	4,600	7,800

Industry scenario A: Low deployment, low EU Production share

- *Direct employment* – By 2030, European production value is expected to be around €54m (€33m PEM and €21m SOFC). Corresponding value-added would be about €15m (€8m PEM and €7m SOFC). The overall European number of employees on the production line related to these activities would be 200 (100 from both PEM and SOFC).
- *Maintenance* – Maintenance would be expected to amount to €5.5m annually[197], employing a further 46. Other horizontal extensions are not included[198].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 120 staff.
- *Trade balance* – Overall trade would be limited, with European component manufacturers exporting to system integrators in all regions, however such systems being imported back into Europe.

Industry scenario C: High deployment, High EU production share

- *Direct employment* – By 2030, European production value is expected to be around €1,200m (€490m PEM and €680m SOFC). Corresponding value-added would be about €360m (€125m PEM and €235m SOFC). Overall European number of employees on the production line related to these activities would be 4,800 (1,500 in PEM and 3,300 in SOFC).
- *Maintenance* – Maintenance would be expected to amount to €71m annually, employing a further 600. Other horizontal extensions are not included[199].
- *Indirect employment* – The production of upstream activities including the provision of inputs such as raw materials and supplies would employ another estimated 2,400 (1,100 in PEM, 1,300 in SOFC).

[197] Assuming maintenance to be 2% of capital costs.
[198] A conservative 1:2 ratio between production and non-production workers would result in a further 400 staff, which are not included in the above tables.
[199] A conservative 1:2 ratio between production and non-production workers would result in a further 9,600 staff, which are not included in the above tables.

- *Trade balance* – Overall trade would be relatively modest but with an export surplus of an expected €100m, as European system integrators would export systems to other regions more than they would import stacks and components.
- In conclusion, commercial CHP has in this scenario important socio-economic impacts. The high system unit costs in relation to the high number of systems produced (12,000 in Europe) lead not only to high GVA but also to high value-added compared to other applications – even when European production and deployment shares have been kept modest in this scenario (14% of global production and 13% of global deployment). The total direct and indirect employment of commercial CHP production are likely to exceed 10,000 jobs by 2030 in this scenario.

Appendix A Dedicated manufacturing and test-bed equipment

Dedicated manufacturing equipment

A further aspect of the supply chain which is essential to its performance and evolution is the availability of appropriate and cost-effective manufacturing machinery and know-how, including quality control. As supply chains evolve and technology and manufacturing matures, different types and scales of machinery, skills and manufacturing layouts are required and high-throughput quality control capabilities are required.

For example, manual assembly of components can be replaced by pick-and-place robots and ultimately by high-speed roll-to-roll machinery in many cases. Small independent ceramic firing layouts can be adapted to continuous process tunnel kilns, or alternative approaches such as high-speed printing and firing can be adopted.

Assessing these capabilities in detail is beyond the scope of this report, but Europe has strong companies and KBAs in many relevant areas, including robotics, high-quality presses and moulds, measuring equipment and others. In some FCH-specific areas it has standard and novel capabilities that are sought globally, for example in bipolar plate manufacture. Broadly speaking, Europe is on a par or leads globally in this area for FCH. Japan in particular has equal strengths.

Dedicated testing equipment

Test and evaluation equipment is also essential to the continued successful development of the supply chain, to validate and improve components and systems, and also to certify them. Generic testing equipment for mechanical, electrochemical, electrical and other types of component are well represented at European level, with world-class companies in many areas. Fuel-cell specific testing capability is dominated by a very few companies worldwide, including German company FuelCon (in the process of being acquired by Japanese company Horiba) and Canadian company Greenlight (in which Austrian company AVL has a stake). AVL has its own developments around fuel cell test systems based around its existing powertrain products. Growth in the FCH supply chain will inevitably drive growth in the test equipment market, and Europe is currently reasonably well placed, but few players exist globally and it is clear that strategic market activity could change the ownership structure relatively rapidly.

Appendix B Nomenclature

AC	Alternating current
AEL	Alkaline electrolyser
AFC	Alkaline fuel cell
AIST	National Institute of Advanced Industrial Science and Technology, a Japanese research facility
ANL	Argonne National Laboratory, operated by the University of Chicago for the US Department of Energy
APU	Auxiliary power unit
BEV	Battery electric vehicle
bn	Billion
BOP	Balance of plant
CCS	Carbon capture and storage
CEA	French Alternative Energies and Atomic Energy Commission
CGS	Compressed Gas Storage
CHP	Combined heat and power
CNG	Compressed natural gas
CO	Carbon monoxide
Comm-CHP	Commercial CHP. Here defined as a CHP system with an electrical output capacity between 5 kW and 100 kW
CRRC	A Chinese publicly traded rolling stock manufacturer
DC	Direct current
DLR	German Aerospace Center
DoE	United States Department of Energy
DoT	United States Department of Transport
EEA	Electrode electrolyte assembly
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPFL	École polytechnique fédérale de Lausanne
EPS	Electro Power Systems S.A.
EU	European Union
FC	Fuel cell
FCEB	Fuel cell electric bus
FCEV	Fuel cell electric vehicle. Application covers passenger cars and light commercial vehicles
FCH	Fuel cell and hydrogen
FISIPE	Fibras Sinteticas de Portugal, S.A. operates as a subsidiary of SGL Carbon SE
fte	Full time equivalent
GDL	Gas diffusion layer
GHG	Greenhouse gas
GM	General Motors Company
GVA	Gross value added
GW	Gigawatt

HGV	Heavy goods vehicle. Truck weighing more than 3.5 t
HRS	Hydrogen refuelling station
HTEL	High temperature electrolyser
ICE	Internal combustion engine
IEA	International Energy Agency
IKTS	Fraunhofer Institute for Ceramic Technologies and Systems
IP	Intellectual Property
JARI	Japanese Automotive Research Institute
JGA	Japanese Gas Association
JM	Johnson Matthey
JSTRA	Japan Ship Technology Research Association
KBA	Knowledge-based actor, e.g. a University
kW	Kilowatt
LCV	Light commercial vehicle. Commercial vehicle such as a van or small truck weighing less than 3.5 t
LGFCS	LG Fuel Cell Systems Inc.
LIB	Lithium ion battery
LOHC	Liquid organic hydrogen carrier
MCFC	Molten-carbonate Fuel Cell
MEA	Membrane Electrode Assembly
METI	Ministry of Economy, Trade and Industry, a ministry of the Government of Japan
MTU	MTU Friedrichshafen GmbH, manufacturer of commercial internal combustion engines
MW	Megawatt
m	million
mCHP	Micro-CHP. Here defined as a CHP system with an electrical output of less than 5 kW
MW	Megawatt
m€	million Euros
NEDO	New Energy and Industrial Technology Development Organisation. Japan's largest public management organization promoting research and development as well as deployment of industrial, energy and environmental technologies.
NMRI	National Maritime Research Institute, Japan
NREL	National Renewable Energy Laboratory,
O&M	Operation and maintenance
OEM	Original equipment manufacturer, typically used to refer to car manufacturers
PACE	An FCHJU project : Pathway to a Competitive European Fuel Cell micro-Cogeneration Market
PAFC	Phosphoric acid fuel cell
PBI	Polybenzimidazole, a synthetic fiber with a very high melting point
PEM	Proton exchange membrane
PEMEL	Polymer electrolyte membrane electrolyser
PEMFC	Proton exchange membrane fuel cell
PSI	Paul Scherrer Institut, the largest research institute for natural and engineering sciences in Switzerland

PTFE	Polytetrafluoroethylene, a synthetic fluoropolymer of tetrafluoroethylene
R&D	Research and development
RIST	Research Institute of Science and Technology, Korea
RTD	Research and technology development
SAIC	SAIC Motor Corporation
SGL	SGL Carbon SE, german manufacturer of carbon-based products
SMR	Steam-methane reforming
SOEL	Solid oxide electrolyser
SOFC	Solid oxide fuel cell
SUV	Sports utility vehicle
SWOT	Strengths, weaknesses, opportunities, threats. A strategic planning technique.
t	tonne
THE	Tianjin Mainland Hydrogen Equipment Co. Ltd.
TRL	Technology readiness level
UNIST	Ulsan National Institute of Science and Technology, Korea
UPS	Uninterruptable power supply
VA	Value added
WP	Work package
xEV	Electric vehicle of any of the following types: hybrid electric vehicle (HEV), plug-in hybrid (PHEV) or battery electric vehicle (BEV)
ZBT	Zentrum für BrennstoffzellenTechnik GmbH