Auto-Stack
PROJECT FINAL REPORT

Publishable Report

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Lead beneficiary: *ZSW*
Prepared by: *André Martin*
Report submitted: *Ludwig Jörissen*
Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg
Tel.: *+49-731-9530 605*
Fax: *+49-731-9530 666*
e-mail: *Ludwig.joerissen@zsw-bw.de*

Project Web-Page *http://autostack.zsw-bw.de*

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1 Executive Summary

The Auto-Stack project combined key European players including automotive OEMs, component suppliers and research organizations in a structured approach to facilitate the development and commercialization of automotive fuel cells in Europe. The consortium assessed ways to identify and reduce the critical barriers for better collaboration between stakeholders and generate a more attractive business case for a European automotive stack industry during pre-commercial and early commercial phases.

Activities did include the development of a common OEM specification and stack platform concept, analysis of the potential for meeting the mid-term technical and cost targets by the European supply chain, establishment of a technology roadmap, assessment of synergies with other applications and finally definition of a business concept for a European stack industry.

Major conclusions of the study are:

- A common stack specification and platform concept across several OEMs is technically feasible. A specification and platform design for mid class vehicles was developed and agreed between the OEMs.
- Packaging is critical for the stack platform concept. It requires high power density of the stack to fit the various volumes and geometries of the individual OEM vehicle platforms.
- Metallic bipolar plates are the sole option to matching the targeted volumetric and gravimetric power density of the stack and offer substantial cost benefits over carbon plates.
- With current MEA-technology, the power density target and the automotive performance requirements are in conflict with the requested ultra-low Pt-loading targets of 0,15mg/cm². Automotive ready MEA-technology foreseeable in 2015-2020 timeframe will most likely require a Pt-loading of at least 0.5-0.6 g/kW.
- High stack power density is an excellent alternative to mitigate limitations of Pt-reduction while achieving automotive performance, durability and cost objectives.
- The proposed platform concept offers technical synergies with other industrial applications and therefore delivers the potential for expanding market volumes during early commercialization phase.
- The stack platform can therefore substantially improve economies of scale, accelerate learning curves, reduce market introduction cost and help establish a more robust market introduction scenario.

The Auto-Stack study demonstrated the benefits of combining expertise between OEMs, supply chain and research players by providing a deeper understanding of the technology status, existing limitations, objectives and priorities for further stack research and development with focus on the critical requirements for commercialization of automotive stack technology. Auto-Stack delivers a guide and navigation tool for better focus of stack related research and commercialization activities in Europe. In order to stimulate coordinated action between stakeholders and deliver material proof of the concept, follow-up activities are recommended.

2 Summary of Project Context and Objectives

Commercialization of automotive fuel cell stack technology is still facing massive investment requirements and substantial business challenges in the years to come. Though major technical achievements were reached in recent years, fragmentation of research and development activities and the consecutive lack of critical mass for automotive stack integration in Europe is a serious threat for future competitiveness of the European supply chain and potentially also for some of the automotive OEMs in Europe.

Captive OEM development activities are currently located in the US, Canada and Japan. Several other OEMs are not even prioritizing the technology in their portfolios, yet. Accordingly, the supply chain and research activities in Europe are remote to the centers of gravity and suffer from the associated strategic uncertainties. Frequent changes of political and public opinion due to a lack of consistent overall strategy on vehicle electrification are generating general reluctance of many investors with regard to industrial engagement in fuel cell technology.

Four major European automotive OEMs, six suppliers and four research institutes therefore established a consortium to analyze the status quo, identify and assess the technical and economic challenges and develop recommendations for facilitating the technology development in Europe.

The consortium coordinated by Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW), Germany consisted of the following organizations:

- Automotive OEM and end users
  - Daimler, Germany
  - Fiat trough Centro Richerche Fiat (CRF), Italy
  - SNECMA, France
  - Volkswagen, Germany
  - Volvo trough Powercell Sweden
- Component suppliers
  - DANA, Germany
  - Freudenberg Fuel Cell Component Technology, germany
  - Solvay, Belgium
  - Solvicore, Germany
  - Umicore, Germany
- Research Organizations
  - CEA, France
  - JRC Institute for Energy, Belgium
  - Paul Scherrer Institute, Switzerland
  - ZSW, Germany

Belenos clean power, Switzerland, has been accepted as an associate member of the consortium during the duration of the project.

The following key actions were identified to deliver the requested data base and determine proper approaches:

- Development of a common OEM stack specification and platform concept
- Assessment of the technical status of the supply chain in Europe
- Establishment of topics and recommendations for research and technology development
- Assessment of technical synergies between applications and associated market potentials
- Recommendations for facilitating the business case.

The fuel cell system requirements as defined by the automotive OEMs are requesting general compliance with the typical properties of conventional ICEs. At least equal performance, dynamics, gravimetric and volumetric power density, durability, robustness, degradation, cold start behaviors and cost are baseline and essential criteria to meet. In order to demonstrate the benefits and superiority of clean propulsion alternatives, these properties need to be complemented by a sustainable fuel concept based on a single fuel and superior efficiencies of the well-to-wheel energy chain.

Based on these requirements and detailed assessments of specific boundaries including but not limited to packaging constraints and hybridization concepts, the common OEM target specification was established and agreed by the participating OEMs. The specification includes conceptual features such as scalability and operational robustness to allow a high degree of operational flexibility in different OEM system architectures and applications. Complemented by a market analysis and technical compliance study of other industrial applications typically summarized under the category “early markets”, several applications with a high degree of technical synergy were identified.

Together with specific volume assumptions and the requested timing for availability of components, the specification delivered the technical input for the supply chain analysis. The analysis focused on the two core stack components, i.e. MEAs and bipolar plates as they determine the critical properties in terms of performance and about 90% of the stack cost. Its objective was to identify the properties and maturity status of automotive ready components by 2015 and 2020 which are supposed to deliver the material basis for mid-term product development. Based on these findings, existing gaps towards the ultimate technical and economic commercialization targets should be identified and recommendations for research topics should be developed in order to mitigate these gaps.

The results of the analysis delivered a set of industry data on current and expected state-of-the-art components available until 2020. The assessment of the associated packaging constraints made clear that high stack power density establishes the most critical technical requirement for a common stack geometry fitting different OEM platforms. Based on these bottom-up data, the common OEM stack specification was established, technical development targets and necessary technical trade-offs were determined and a generic stack design was developed. The gap analysis was then used to identify, select and prioritize research topics for mid and long-term research activities to address existing deficiencies.

On top of technical information, the supply chain analysis delivered industrial cost data based on proposed volume assumptions for 2015 and 2020. These data, complemented by progress ratios (learning curve assumptions), were utilized to establish the Auto-Stack cost model, provide cost assessments at component and stack level and assess compliance of the generic stack design with automotive target cost. This did include economic benchmark of technical options to achieve a commercially compatible stack design.

The results of the technical analysis were consolidated in the form of a technology roadmap specifying the requirements for advanced components, the timing for their achievement and the injection points to product development. The stack development plan comprises two product iterations to reach commercial product level. While the design concept of the first iteration is based on state-of-the-art technology with moderate research contributions, the second design iteration will include research results supporting advanced stack properties based on the technology roadmap.

The Auto-Stack business plan finally represents the combined technical and economic considerations for the establishment of a venture. Core elements of the business plan are the stack learning curve, the staff development plan including required core competences, organization charts and description of key functions, an investment plan, projected cost of operation, sales projections and price sensitivity scenarios. Based on these considerations, a profit & loss sensitivity analysis was developed with best and worst case assumptions for breakeven and the required cash flow to reach this objective.

The results of Auto-Stack therefore deliver a complete tool box to help navigate companies and decision takers through a complex and challenging environment and thus facilitate and accelerate automotive fuel cell stack development in Europe. It can provide orientation to the supply industry, help OEMs to reduce investment efforts, provide risk mitigation approaches and a fact base to tailoring research, development and business activities. It therefore provides an essential contribution to consolidating the commercial introduction of fuel cells in transport and other applications in Europe.

3 Description of S&T results

3.1 Work Package 0 - Coordination

The coordination of the project was facing several challenges towards reaching the ultimate project objectives. Facilitation of OEM communication and agreement towards a common specification and platform concept was by far the most critical milestone and achievement in this context.
The results of the supply chain analysis did require a deeper analysis of the technical constraints and priorities of further stack development in order to establish proper and realistic technical targets and determine the pathway to achieving ultimate target cost. The resulting conclusions then had to be translated into a technology roadmap and business concept.

The project hence did require a sequence of assessments as well as analysis of specific issues to establish the necessary fact base, establish solid conclusions and determine realistic technical and economic targets. Amongst them, the analysis of power density requirements versus Platinum reduction targets represented the most critical and challenging part. It provided new insights to the technical constraints and priorities of automotive stack development and helped establish a more streamlined and realistic development strategy towards reaching the technical and commercial targets.

Top down target setting by the project steering committee had to be verified by bottom-up analysis. The results had to be validated, balanced and structured with regard to their relevance and impact. Finally, conclusions had to be translated into proper actions and plans.
During the assessments, several internal and public workshops were held to facilitate the associated discussions, share results and ensure overall alignment of the findings. Specific thematic discussions within or between work packages were used to facilitate communication and help shape conclusions. Regular meetings and conference calls of the steering committee and the consortium provided updates of the status, a platform for overall agreement and orientation for further project activities.

3.2 Work Package 1 - OEM Stack Platform

3.2.1 System Requirements

The fuel cell stack platform was developed in a top down approach, i.e. the requirements of state-of-the-art passenger vehicles were broken down and translated into specific fuel cell stack requirements. Simultaneously, these requirements were mirrored versus state-of-the-art stack technology as specifically reported in section 3.2.4 of this report. This approach was chosen to ensure that the suggested system specification and stack design have a high degree of maturity and can directly be utilized for mid-term industrial product development. Particular attention was paid to the stack target cost, which is seen as the major remaining hurdle for widespread market introduction of fuel cell technology in automotive markets.

Whereas the internal combustion engine today covers all drive cycles and ranges, hybrid and battery electric vehicles have their particular strengths and weaknesses and therefore fit specific segments and requirements, only. The fuel cell propulsion system though is closest to the ICE in terms of its universal fit to a variety of vehicles and driving profiles.

Figure 1 below displays the typical segments for each propulsion system based on these characteristics.

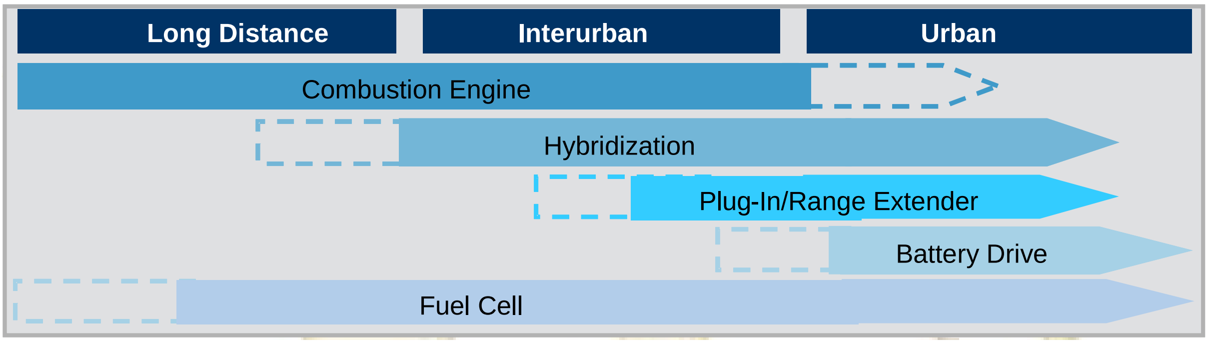


Figure 1: Range of driving profiles of various power trains

Based on the segmentation in Figure 1, corresponding target vehicle types were selected which are suitable for state-of-the-art fuel cell propulsion. The OEMs agreed on a compact class vehicle (Golf, VW) as the reference case for this project. It should however be noted, that ongoing developments aim at more powerful and larger cars for longer ranges, too. Figure 2 below provides an overview of the analyzed and targeted vehicle categories for state-of-the-art fuel cell application.

	Micro-Kompakt	Kompakt-Klasse	Mittel-Klasse	Luxus- & Familien-Fzge	City-Bus	Überland-Bus	Klein-laster	Mittlerer LKW	Schwerer LKW
FC-EV	yellow	green	yellow	yellow	green	red	green	yellow	red
B-EV	green	yellow	red	red	red	red	yellow	red	red

green: possible — yellow: Possible with restrictions — red: Today not possible

Figure 2: Suitability of Battery / Fuel Cell Drive Train for Various Vehicles

The vehicle requirements then were cascaded into fuel cell system requirements. The basic requirements on system level were agreed as follows:

- Performance, dynamics
- Gravimetric and volumetric power density
- Durability, robustness, degradation
- Cold start, cold start time
- Limitation to one fuel
- Cost

Generally, comparable to ICE

These need to be complemented by:

- High efficiency
- Sustainability of fuel concept

Superior to ICE and Hybrids

Based on the system requirements, the common system architecture had to be established. The objective was to enable a joint stack platform concept while at the same time allow sufficient flexibility for different system architectures and operation strategies of individual OEMs.

The OEMs therefore agreed on the following essential system properties and components only:

- Net power output of 80 kW
- Scalability of the stack for different power levels
- Agreement on system architecture limited to:
  - Air compressor without expander
  - Gas-to-gas humidifier (cathode out ⇒ cathode in)
  - H_2 - recirculation pump (active ⇒ blower or passive ⇒ jet pump).

The simplified flow diagram of the system is displayed in Figure 3 highlighting the gas-to-gas humidification via a membrane humidifier and the hydrogen loop.

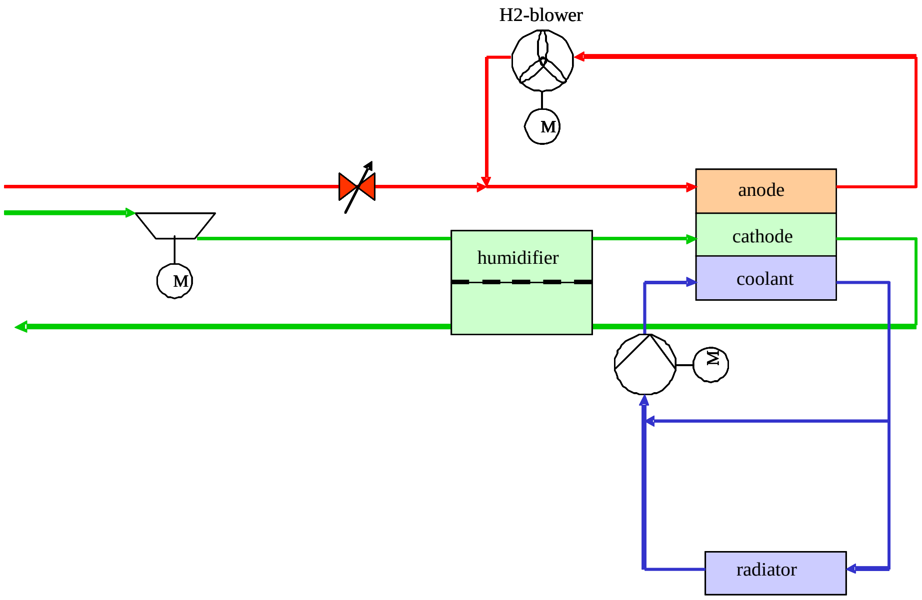


Figure 3: Simplified schematic of the automotive fuel cell system

3.2.2 Stack Specification

In order to determine a consistent scope of activity, the term "stack" was defined comprising the following components:

- Bipolar plates, MEA, sealing
- Current collectors + end plates
- Stack compression kit
- Casing / Housing (also for the purpose of electromagnetic compatibility)
- Flanges and (quick) connectors
- HV-contactors + interlock
- Vehicle mounts (brackets)
- End cell heaters (PTCs)
- Sensors.

Other components such as hydrogen leakage sensors, stack box ventilation (active or passive), hydrogen shut-off valve and air shut-off valves for electrode protection (optional) are considered part of the fuel cell power system. The stack shall have a self supporting structure and not require structural support of or to the vehicle.

Reflecting the system requirements, the following high level stack specification was developed and agreed:

- Power density
  - High operating point: 1,5 A/cm²@ 0,675 V/cell
  - Low operating point: 0,2 A/cm2 @ 0,8 V/cell
- Stack efficiency
  - High power: 51 %
  - Low power: 61 %
- Pt – Loading
  - Low risk approach: < 0.6 mg/cm²
  - Medium risk approach: 0.4 mg/cm²
- Stack-power 95 kW, scalable 10 – 95 kW or multiples
- Operating Temperature < 95° C
- Operating pressure < 2 bar_a
- Voltage 220 - 430 V
- Power density (95 kW stack) < 60 l / 75 kg
- Cost 101 €/kW @ 10,000 *95 kW stacks
- Durability beyond > 5000 h.

The definition of the specification targets was based on the assessment of component availability and specification properties until 2020. More details of the supply chain assessment are available in section 3.3 of this report.

The OEMs agreed that front packaging will be required to provide sufficient flexibility for the integration of different propulsion systems in the same vehicle platform, at least until 2025. The analysis of the associated packaging constraints of individual OEM vehicles made clear that high stack power density in terms of performance, volume and geometry establishes the most critical technical requirement for the common stack platform. As result of the packaging analysis, a joint geometry was determined for the fuel cell stack and subsequently for the single cell shape. The actual motor compartments for front packaging of representative actual OEM vehicles (Daimler: E-class, Fiat: Panda, VW: Jetta) are displayed in Figure 4 – below.

The packaging constraints are forcing high power density with a performance of at least 1 W/cm2 under typical automotive operating conditions. The automotive fuel cell stack has to combine high power density with low cost, high reliability, high efficiency and sufficient durability.

The most critical analysis in that context circled around the issue of MEA Pt-loading. In essence, precious metal loading is frequently used as a descriptive parameter to achieve the ultimate stack target cost which is needed for commercialization, i.e. $ 35 – 40/kW. This cost target is typically tied with the assumption that MEAs should contain less than 0.15 mg Platinum per cm^2 active area to achieve this cost target (see DoE[1] and others).

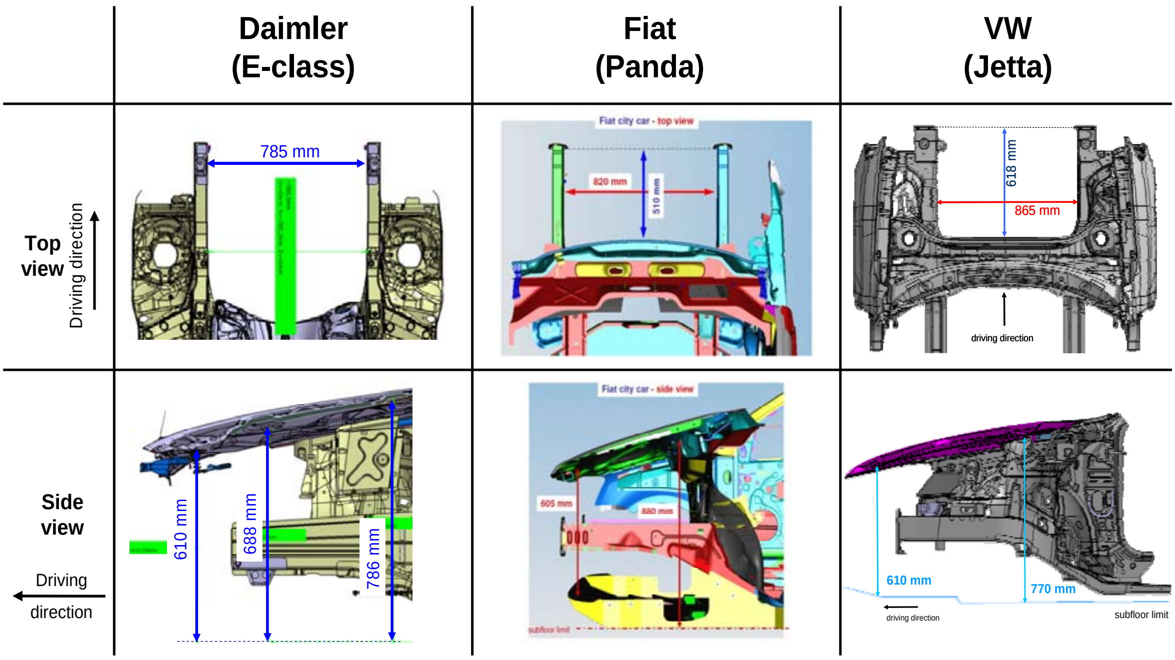


Figure 4: Comparison of front package volumes for selected OEM vehicles

The supply chain assessment and more specific analysis of the associated issues however suggested that simultaneous achievement of ultra-low Pt-loadings and the targeted power density (1 W/cm2) at the requested efficiency (>670 mV per cell) constitutes an enormous challenge. The target is even more critical in the kinetic stack region at low current density, where the catalyst layer is already fully used with the higher Pt-loadings today. Any further reduction of Platinum will therefore directly impact stack efficiency which is considered a no go for automotive operation.

[1] http://www.annualmeritreview.energy.gov/

Based on experimental data, a logarithmic correlation between Pt - loading and power density is assumed for all MEA technologies. The graph below shows the resulting stack costs in €/kW for the 2015-MEA at different price constellations. It appears that besides technical limitations of current MEA-technology, the optimum Pt-loading under cost aspects may be in the region of 0.4mg/cm² as this would allow the best balance between all conflicting requirements and provides the best trade-off between the cost of the Platinum and area cost of the stack.

In effect, automotive ready MEA-technology foreseeable in the 2015 to 2020 timeframe will therefore most likely require a Pt-loading of at least 0.5-0.6 g/kW. It is assumed that such Pt-loading represents the technical limit of current MEA-technology while still fulfilling technical application targets. It should however be recognized that even this target still needs to be proven under automotive operating conditions.
The graph in Figure 5 below displays the balance of power density and Pt-loading under different area specific cost assumptions (i.e. membrane and bipolar plates) using a Pt-price of € 30/g.

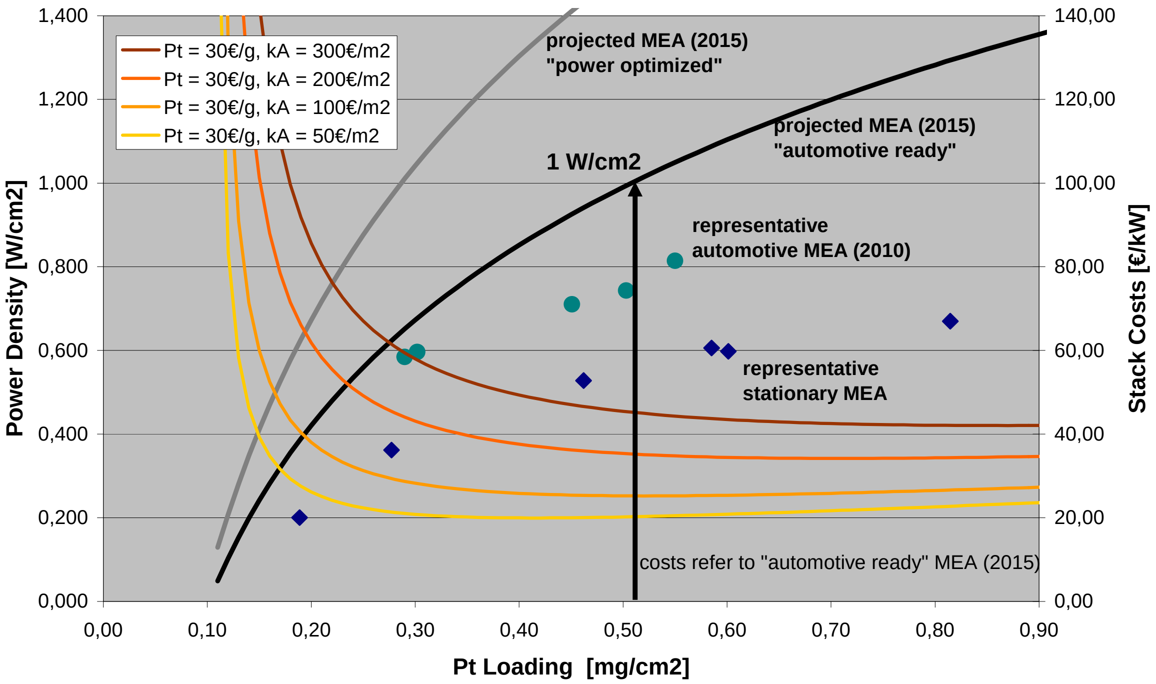


Figure 5: Balance of power density and Pt-loading and their relative cost impact

3.2.3 Functional and Validation Testing

During vehicle life, the stack will be faced with all kinds of different driving, climate and other environmental conditions. In order to prove the design concept and specific properties of the stack, a set of typical automotive tests were determined and agreed between the OEMs with degradation testing being the core of it. Since stack degradation does not simply scale with mileage and calendar age but is primarily determined by the load spectrum, i.e. the frequency of detrimental operation modes, critical operating conditions were identified and respective tests determined.

Durability testing does include and selectively stress those adverse conditions such as:

- Hot operation
- Start/Stop
- H_2 depletion
- Reactant impurity effect (SO_2, NH_3, CO, NO_x).
- Pressure Swing
- Freeze Start…

In Figure 6 below, critical stack operating conditions, so called “stress factors” of the drive cycle, with impact on stack durability and degradation are displayed.

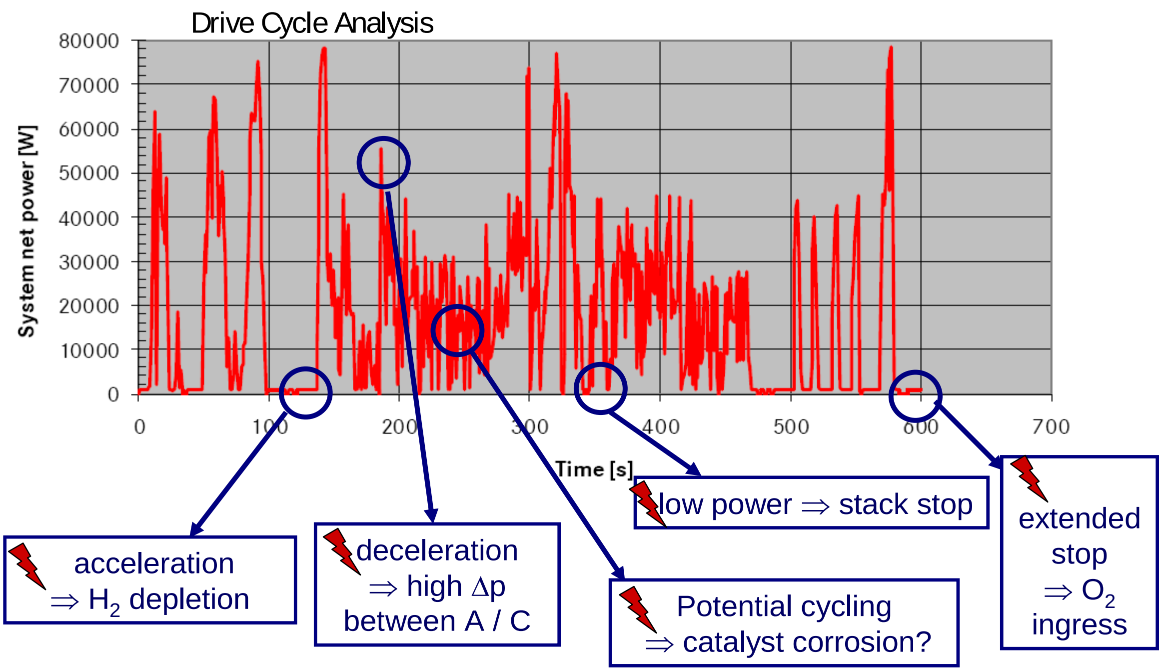


Figure 6: Stress factors in a “real” drive cycle

The OEMs agreed a maximum power loss of 10% or end-of-life max power of 0.9 W/cm². However, degradation should not lead to increased heat release from the stack. The respective end-of-life cell voltage would be 0.637 V and the end-of-life current density 1.413 A/cm². This requirement compares to typical specifications for ICEs.

3.2.4 Application synergies

The stack specification was established to fully meet automotive application requirements but also allow operation in other applications. In order to address the individual power and application requirements of these applications, the stack power can be scaled from 10 kW to 95 kW or multiples thereof by changing cell count, combining two or more stacks or by means of DC/DC converters as the case may require.

An assessment of the technical compliance level and a market analysis carried out in Auto-Stack identified several applications with a high technical compliance level. The details of this analysis are described in section 3.5.3 of this report.

3.3 WP 2 - Supply Chain, Cost Model and Research Needs

In work package 2, technical properties and commercial availability of PEFC components for the Auto-Stack platform were analyzed with a bottom-up methodology. The purpose of this analysis was to identify state-of-the-art industrial components thus to establish a realistic mid-term stack specification which can be supported by the supply chain.

The scope of analysis was determined as follows:

- Only European suppliers of PEFC stack components were analyzed.
- Only stack repeating components were investigated, i.e. MEA, bipolar plate and sealing.
- Balance of stack parts such as endplates or compression kits were excluded.
- The component specifications were restricted to the requirements of Auto-Stack.
- Cost estimates were requested for production volumes between 250 - 25.000 stacks/year, in 2015 and 2020, respectively.

The analysis focused on the stack repeating units only since they determine the technical status and about 90% of mass production cost. The search did involve 54 companies with headquarters or operations in Europe, with 22 of them being considered particularly relevant in terms of technical status and industrial engagement. The feedback in this latter group was 73%. Unfortunately, a few important players did not respond to the questionnaire. The response rate was nevertheless extraordinary good and the results are believed to establish a solid picture of the status of European supply chain. For confidentiality reasons, only general findings are presented in this report.

3.3.1 Technical assessment – MEA

Relevant surveys such as the ones initiated by the U.S. DoE[2] and executed by TIAX[3] and DTI[4] are assuming a target of 0.15 mg/cm^2 platinum loading to achieve the commercial cost target of 35 $/kW for the automotive fuel cell stack. For the purposes of the Auto-Stack supply chain survey, this was combined with the requested specific performance of 1.5 A/cm^2 at

[2] Progress of the U.S. DoE sponsored Hydrogen and fuel cells program is available from http://www.annualmeritreview.energy.gov/
[3] Se for reference: http://www.hydrogen.energy.gov/pdfs/review10/fc019_sinha_2010_o_web.pdf
[4] http://www.hydrogen.energy.gov/pdfs/review10/fc018_james_2010_o_web.pdf
http://www.hydrogen.energy.gov/pdfs/review11/fc018_james_2011_o.pdf

a cell voltage of 670 mV as per the Auto-Stack specification to establish a consistent and relevant reference which would be meeting the automotive application targets.

The results of the inquiry document, that the requested specific performance of 1.5 A/cm²@0.67 V = 1 W/cm² with the target Pt-loading of 0.15mg/cm² cannot be achieved by any supplier when observing durability, robustness, efficiency and degradation targets necessary for automotive application. Moreover, no projections were made by the relevant companies for development of the specific performance in the timeframe 2015 to 2020. In figure 8, next page, the results of the technical assessment of MEA properties are displayed.

As this was a very critical finding, broader scouting of literature and the internet was done to find out whether there are any relevant data either confirming or challenging these results. Despite research activities around the globe, no data were found fulfilling the requirement under the relevant operating conditions.

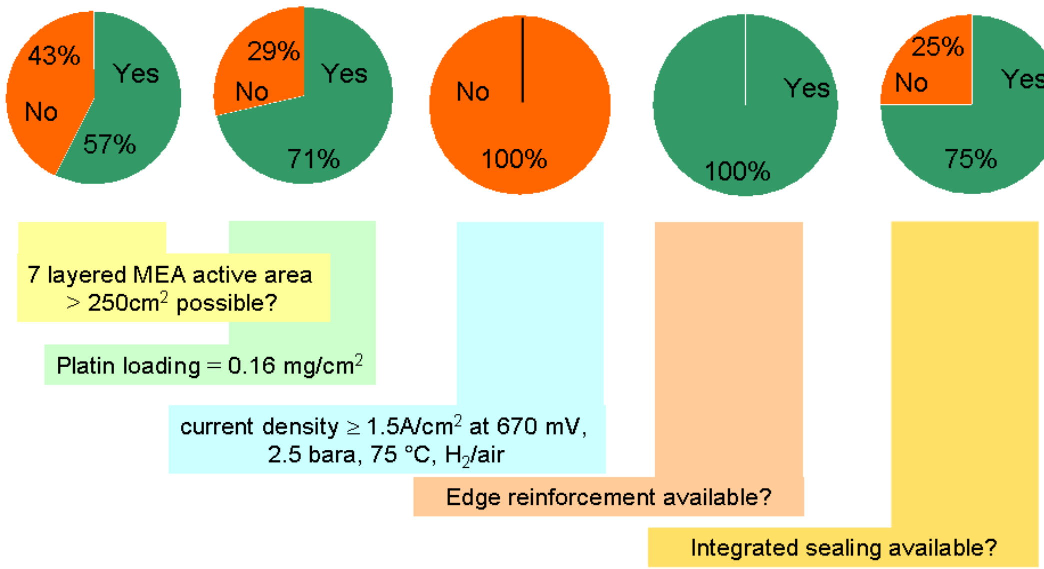


Figure 7: Results of the technical analysis - MEA

As consequence, substantially higher Pt-loadings will have to be used with available industrial MEA-technology at least until 2020, unless new innovative electrodes or electrode materials will be developed and introduced. But even if such materials can be successfully developed, introduction will require many years before reaching the performance criteria and maturity level required in the automotive industry.

Therefore, a trade-off analysis was done to identify whether there are other ways to mitigate the negative impact of higher Pt-loadings on stack mass production cost. The results of this analysis provided insight to the fact that substantial optimization potential exists at stack level to limit and balance the negative effects. The associated considerations, the result of additional assessments and the relevant conclusions are reported in section 3.4 of this report.

3.3.2 Technical assessment - bipolar plates

Bipolar plates have a massive influence on stack power density, performance and durability. They also establish a key cost factor in terms of area cost of the stack. The objective of the assessment was therefore to identify whether state-of-the-art components can support the Auto-Stack development targets and what the differences between metallic and carbon bipolar plates are in this respect.

The cell pitch for the survey, i.e. the distance between one cell and another, was specified with < 2 mm. The final Auto-Stack specification is however < 1.2 mm. This specification was however not yet available at the time of the supply chain analysis. The sealing was considered to be part of the bipolar plate.

The results of the analysis document, that the required cell pitch of < 2mm could not be fulfilled by any of the European carbon bipolar plate suppliers but by all suppliers of metallic bipolar plates. The minimum web thickness indicated for carbon bipolar plates is about 0.8 mm while it is ~ 0.1mm for metallic bipolar plates. In Figure 8 and Figure 9 below the results for metallic and carbon bipolar plates are displayed.

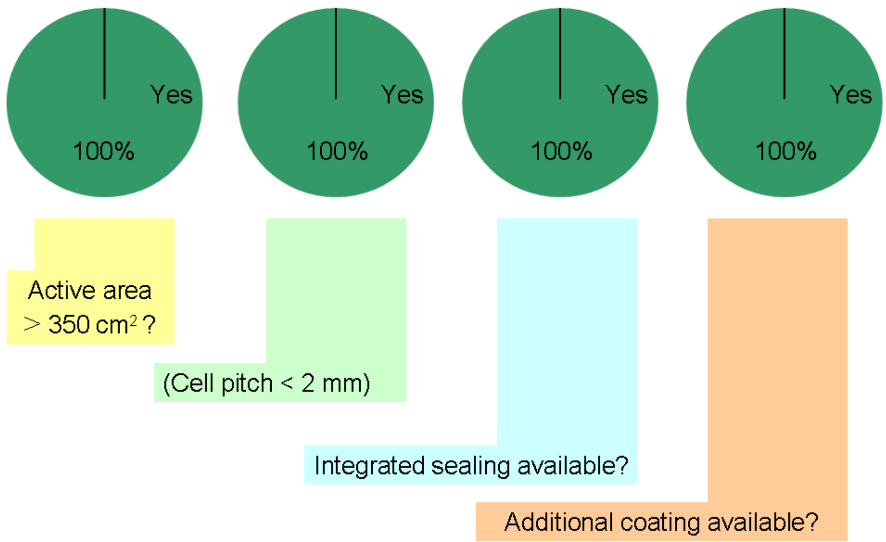


Figure 8: Results of the technical analysis of metallic bipolar plates

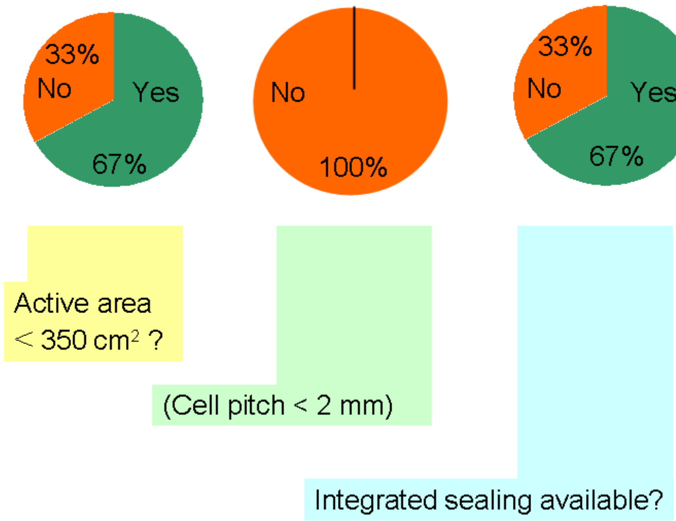


Figure 9: **Results of the technical analysis of carbon bipolar plates**

Data from extra European suppliers suggest that carbon bipolar plates can be produced with cell pitch < 2.0 mm but even then, a major gap to the final specification target of < 1.2mm remains which apparently can only be achieved with metallic bipolar plates.

Though, the technical benefits identified by the analysis privilege metallic bipolar plates over carbon bipolar plates, the survey also discovered a general lack of expertise with regard to material properties such as electric and thermal conductivities and in particular of coating and sealing technologies by most of the metallic bipolar plate suppliers. While these elements can typically be provided via specialized sub-contractors, a lack of total process expertise was visible and establishes a threat for the availability of mature and robust stack components from European sources.

At the time of the assessment, only one European supplier owned the required overall expertise and was able to offer fully integrated metallic bipolar plates with the required technical maturity. Given the critical impact of this expertise with regard to achieving overall stack performance, durability, manufacturability and cost, this was a more than astonishing and disappointing result.

3.3.3 Cost assessment

The supply chain assessment did include cost projections for the time frame 2015 and 2020 based on the production volume assumptions shown in the following tables. For the specific power and the size of the active area of the stack, the following assumptions were used:

- 1 W/cm^2 specific power density at 0.67 V cell voltage of the MEA
- 95 kW gross stack power
- 315 cells per stack
- 300 cm^2 active area per cell.

The MEA cost estimates have been asked from the suppliers for 5-layer type MEA's with the initially proposed Pt-loading of 0.15 mg/cm^2. As Pt-reference cost, 40 €/g Pt were used. This Platinum price is different from the DTI assumption (35 \$/g (equaling 25 €/g) Pt) [1], but seems more realistic observing the Platinum price history and current price level. The estimate is for per-fluorinated membranes. Cost for sealing was not included as it was chosen to be part of the bipolar plate. The cost is quoted as €/kW based on the outlined assumptions.

Production cost [per kW_{stack}]	Mean value	Lowest value	@ annual production rate [unit]	Production capacity [units]
2010	124 €	71 €	100.000	10 – 300 k/a
2015	62 €	14 €	1mill	0.1 – 1mill/a
2020	44 €	14 €	4mill	n. a.

Table 1: **Cost projections for MEAs**

A metal bipolar plate is composed of two half plates, including coating and sealing. The data in Table 2 are for a complete plate with an active area of 300 cm^2. If coating was not included in the cost quoted by the supplier, a markup of 1 €/plate was assumed. This value was derived from the TIAX study [2] which uses ~0.4 €/plate for nitrification coating process applying a more conservative approach.

Production cost* [kW_{stack}]	Mean value	Lowest value	@ annual production rate [unit]	Production capacity [units]
2010	44 €	37 €	100.000	10k – 10mill/a
2015	18 €	15 €	1mill	0.5 – 12mill/a
2020	11 €	8 €	10mill	5 – 100mill/a.

Table 2: **Cost projections for metallic bipolar plates**

A carbon composite bipolar plate is composed by two half plates and sealing. The data in Table 3 are for a complete plate. If sealing was not included in the cost by the supplier, an additional cost of 1.5 €/plate was assumed. This value was conservatively derived from a source within the consortium.

Production cost* [kW_{stack}]	Mean value	Lowest value	@ annual production rate [unit]	Production capacity [units]
2010	87 €	32 €	100.000	35 – 200 k/a
2015	42 €	27 €	1mill	1 – 2mill/a
2020	20 €	12 €	10mill	10 – 100mill/a

Table 3: Cost projections for carbon composite bipolar plates

Cost projections for bi-polar plates @ mass production, i.e. 10 million plates, received within the survey suggest that the cost of metallic versus carbon bipolar plates is between 33% (average) and 45% (maximum) lower. Thus metallic bipolar plates not only offer better technical properties but also cost benefits over carbon plates.

3.3.4 Cost modeling

Following the approach of the supply chain analysis, the methodology of the "Cost Evaluation Tool" was based on the core stack components having the most critical cost impact. The assumed production rates were: 1 000, 10 000, 50 000, 100 000 and 500 000 fuel cell stacks per year. Due to the lack of industrial data, a part of the production rates, i.e. those above 50 000 stacks / year could only be calculated through extrapolation of component costs by applying relevant learning curves. For reference and benchmark purposes, relevant other studies were observed. The general approach of the cost model is displayed in Figure 10, below.

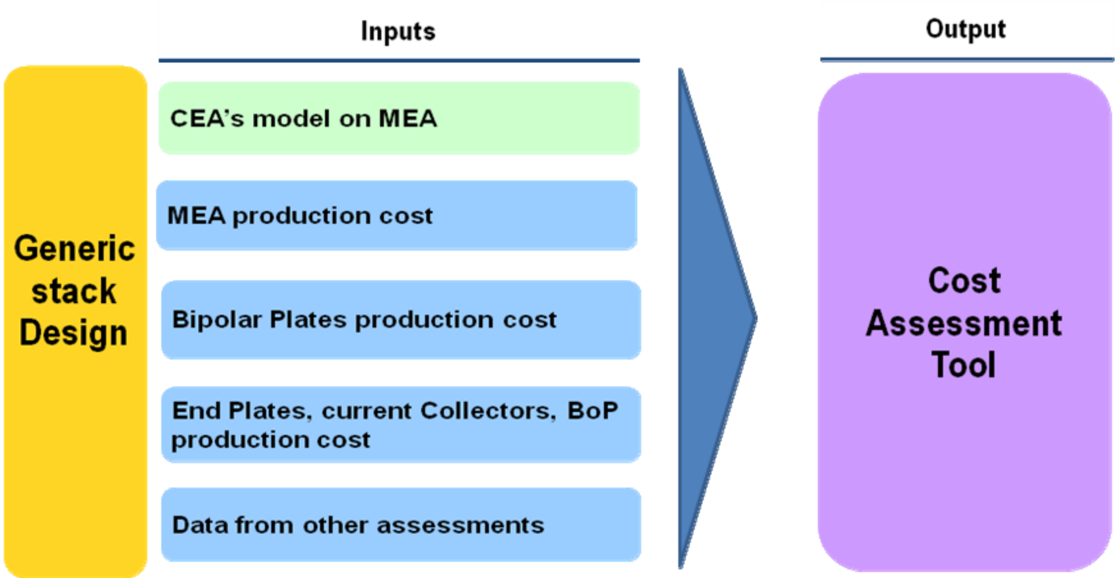


Figure 10: General approach of the cost model

The reference design for the cost analysis was chosen with a conservative approach assuming no progress of Pt-reduction in the mid-term. Along with the reference design, more challenging design options were investigated and calculated to understand the sensitivity of stack cost versus design options and different Pt-loadings.

The cost modeling confirmed the assessment of empirical data delivered by the supply chain analysis. Metallic bipolar plates deliver significant cost benefits over carbon bipolar plates establishing an advantage of ~ 27% at optimum production rates. The results of the cost analysis for the reference design are shown in Table 4, next page.

More importantly, the aggressive power density target of the Auto-Stack specification seems to providing an alternative way towards reaching automotive target cost while fully matching the performance and durability requirements. The per/kW-stack cost of € 44.00 @ 500 000 units as result of the Auto—Stack cost modeling complies very well with similar assessments such as the power-train study supported by the European Commission and a consortium of relevant automotive OEMs. Assuming a production capacity of 1 000,000 fuel cell vehicles by 2020, the stack cost was forecasted with € 43.00/ kW in this study.[5] Contrary to the Auto-Stack assumptions, the assessment was assuming very aggressive Pt-loading reductions down to a level of only 0.24 g/kW.

Annual production rate	1000	10000	50000	100000	500000
Total stack cost - mBPP	16 187 €	9 608 €	6 781 €	5 853 €	4 187 €
Cost/kW gross - mBPP	170 €	101 €	71 €	62 €	44 €
Total stack cost - cBPP	18 971 €	11 791 €	8 508 €	7 398 €	5 359 €
Cost/kW gross - cBPP	200 €	124 €	90 €	78 €	56 €

Power density 1 W/cm²
Pt-price @ 21,1€/g
Stack power 95 kW
Total Pt-loading 0,85 mg/cm²

Cost benefits of metallic BPP vs. Carbon BPP = 27 % @ optimum production volumes

Table 4: Results of the cost model – reference design

[5] *"A portfolio of power-trains for Europe: a fact based analysis"*, McKinsey & Company, Nov 2010, page 60

3.3.5 Research needs

The findings of the supply chain analysis described in the previous section are highlighting some critical gaps with regard to achieving the technical objectives of automotive stack development. With current MEA technology, ultra low Pt-loadings of 0,15mg/cm² cannot be achieved under the relevant automotive operating conditions. Besides the fact that performance targets will be missed, stack area specific cost will be significantly increased almost outweighing the cost benefits of lower Pt-loadings.

The assessment therefore suggests that high power density has to be the outstanding development target. Only then, common standards can be established, performance targets will be achieved and cost targets can be meat. Industry data suggest potential Pt-loading reductions down to 0.5 – 0.6mg/cm² at the requested power density and performance, until 2020, while the optimum under technical and economic considerations seems to be in the vicinity of 0.4 mg/cm².

Based on the findings of the survey and general assessment of the stack development status, a total of 10 research topics were identified and prioritized by the consortium for short term, medium term and long term research activities. These priorities are listed in Table 5, next page.

Forced by the fact that lower Pt-loadings will fail automotive specification requirements, the stack specification assumes Pt-loadings of 0.6…0.4 mg/cm² based on current technology. While 0.6 mg/cm² is considered a midterm target with significant probability to meet the performance efficiency and durability requirements, 0.4 mg/cm² still establish a challenge with substantial development risk.

Research Priorities for Automotive Stack Development		
Short Term	**Mid Term**	**Long Term**
Development of a full size automotive stack based on the Auto-Stack roadmap	Development of advanced MEA with increased power density, optimized Pt-loading, lower humidification requirements and elevated operating temperature	Material research on non noble catalyst materials for replacement of Pt-group metals
Development of optimum power streams in fuel cell systems with improved balance of fuel cell power and energy storage	Development of advanced low-cost, corrosion resistant and highly conductive bipolar plates with particular focus on coating and integrated seals	Development of a multi-scale modeling tool for MEA performance with focus on transport and aging phenomena
Development of industry wide uniform performance test schemes and commonly accepted test protocols	Development of cell modeling for accelerated stack design with focus on critical operating parameters	Development of stack concepts for simplified fuel cell system architectures and improvement of scale effects
	Development of characterization techniques for water management and state of health at cell and stack level	

Table 5: Research Topics identified by Auto-Stack

It is therefore concluded that mid-term technology development should focus on achieving high power density in combination with continued optimization of efficiency, improved catalyst utilization and enhancement of robustness and durability. In the long term development of new PGM-catalysts and catalyst materials as well as novel electrodes will be required to further reduce Pt-loadings to the target levels. For industrial purposes, such novelties seem however not to become available before 2020.

3.4 Work Package 3 - Technology Roadmap

3.4.1 Interfaces and input

The Auto-Stack technology roadmap builds on the OEM specification and platform concept and reflects the results of the associated assessments which were described in the previous chapters. The roadmap assumes a collaborative approach of OEMs, suppliers and research partners in combination with a system integrator. The entire product development will require two product generations for reaching ultimate specification requirements.

Figure 11 below shows the overview of interfaces and inputs for the establishment of the roadmap.

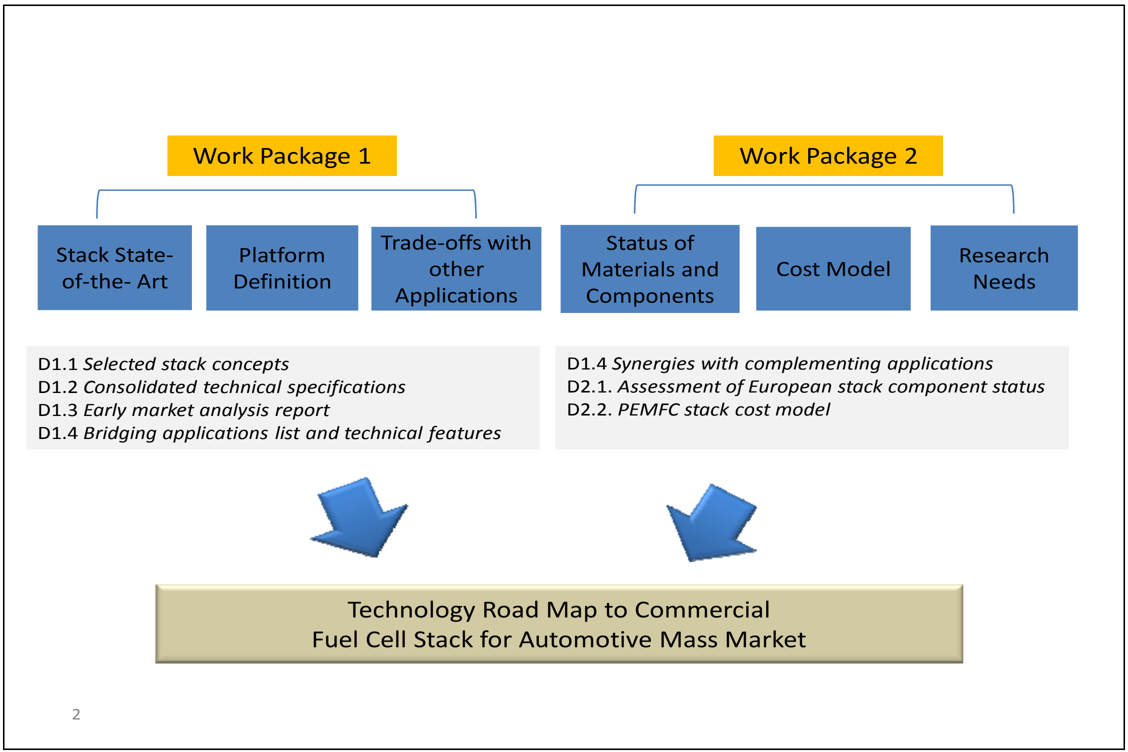


Figure 11: Overview of interfaces and inputs to the technology roadmap

3.4.2 Product development plan

The first generation stack development plan is based on today's state-of-the-art materials and components and shall provide proof of concept. It is assumed to serve volumes of a few thousand units at the maximum thus facilitating early commercialization from 2015. The development process is divided into five phases, each starting and ending with a gate. The successful passing of the gates will trigger the next phase. All phases indicate a certain focus and maturity level of the product development.

The Auto-Stack study establishes the initial milestone as prerequisite for starting the first generation stack development. The master schedule of the 1st generation development plan is displayed in Figure 12– below.

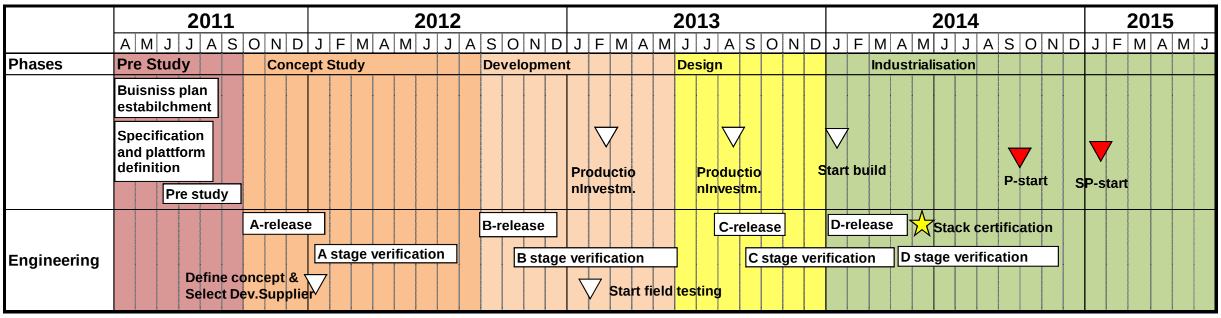


Figure 12: 1st generation development plan

The second generation product development plan is targeted to support mass production volumes > 10 000 units. It therefore has to fulfill all OEM requirements. It shall be based on advanced material and components developed in the timeframe 2011-2014 and will start with the pre-study phase from 2014 to verify and consolidate the advanced platform concept. Start of mass production is assumed for 2018. The master schedule of the 2nd generation development plan is displayed in Figure 13 – below.

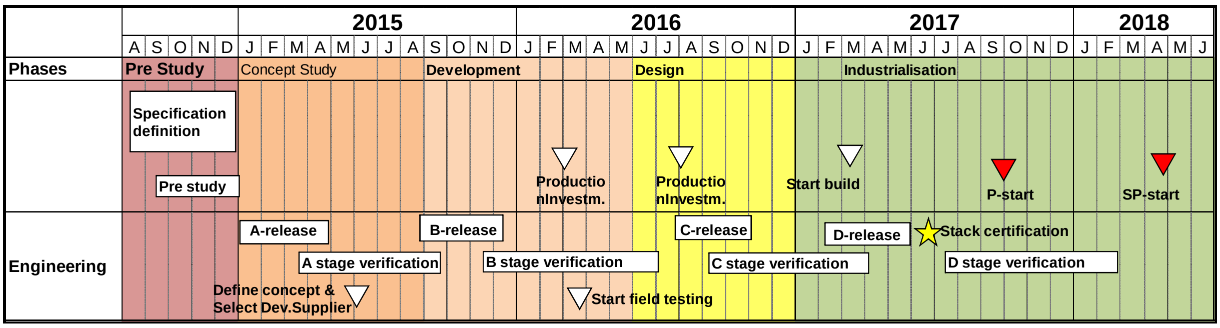


Figure 13: 2nd generation development plan

3.4.3 Research activities

Considerable R&D on components and materials will be needed during the 2011 to 2015 timeframe to meet the specification requirements of the phase 2 product as described above. For this, advanced component specifications were generated and injection points to the product development plan were determined to support the second generation development targets. The associated research priorities are contained in Table 5, above.

The breakdown and alignment of research activities at component level and their respective timing is monitored in Table 6 below.

Stack component	2012	2013	2014	2015	2016
Bipolar plate (Gen1)					
Bipolar plate (Gen2)					
End plate Gen 1					
End plate Gen 2					
Current Collector					
MEA Gen 1					
MEA Gen 2					
GDL Gen 1					
GDL Gen 2					
Stack sealing Gen 1					
Stack sealing Gen 2					
Housing					
Insulation					
Fluent connectors					
Stack assembly Gen 1					
Stack assembly Gen 2					

Table 6: Alignment and timing of R&D activities at component level

3.4.4 Master plan

The master plan finally combines all product development and R&D activities in one consistent schedule. It delivers the integrated pathway of all development and research actions, the full product development cycle and the overall rationale of the technology roadmap. The generic master plan and product development cycle is displayed in Figure 14 - below.

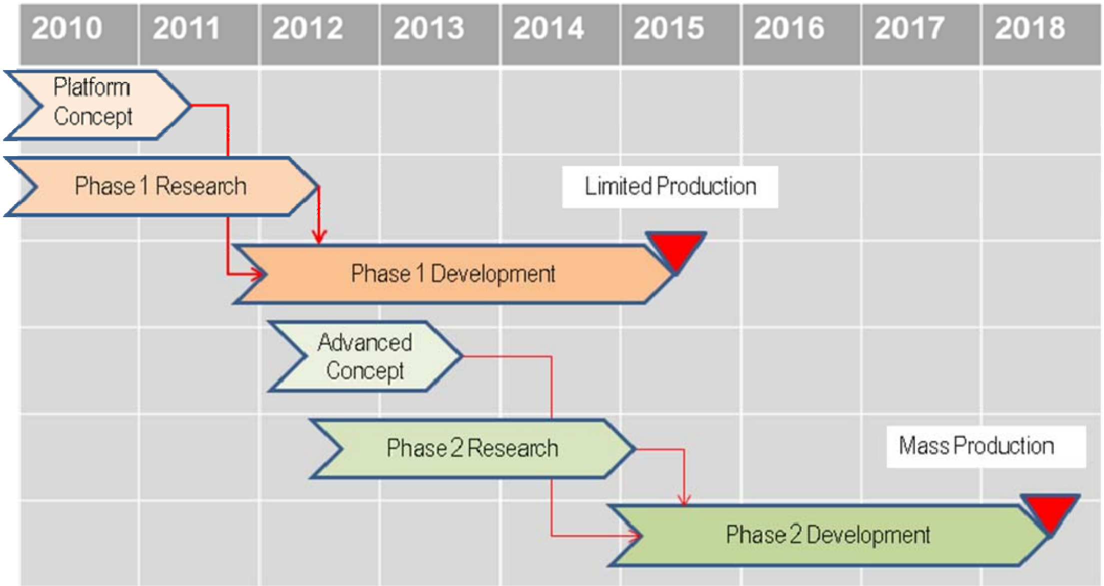


Figure 14: Master plan and product development cycle

Key milestones representing development gates towards the final objective are essential elements of the technology roadmap. While several of them were part of the scope of Auto-Stack and were consequently addressed by the project, others shall be subject of follow-up activities. Amongst them addressed in the project are: fixing specifications, application targets and goals, prioritizing technical and commercial parameters, developing trade-offs between conflicting targets, establishing the platform concept, evaluating technical synergies and developing advanced component specifications. Those milestones reserved for follow-up activities are stack development, validation and manufacturing based on the design, selection and validation of components as described in the master plan.

The technology roadmap delivers a well grounded and consistent tool, to translate the results of the study into hardware and implement the findings in real action. The roadmap provides guidance and navigation for shaping and scheduling research topics of the FCH JU research agenda and the MAIP thus supporting better focus and target orientation of research European activities.

3.5 Work Package 4 – Business Model for Stack Integrator

3.5.1 Strategic considerations and assumptions

The business model proposed by Auto-Stack is based on a number of key assumptions establishing the framework for a potential stack integrator:

- Stack development will be focused on a platform concept suitable for different OEMs and vehicles.
- The stack integrator shall concentrate on core activities in stack development, validation and manufacturing.

- Cooperation with strategic research partners, suppliers and OEMs will complement these core activities.
- The joint technology roadmap establishes the overall technical objectives and pathway towards reaching the technical objectives and an integrated approach for the collaboration.

The complexity and inherent challenges of the technology development and the associated commercialization activities will require a step approach to properly manage technical and commercial risks, control the level of investment and allow conceptual adjustments when and where needed.

3.5.2 Unique value proposition

The proposed product specification and platform concept is reflecting the joint technical assessment of four major OEMs, key suppliers and leading research institutes. It is result of an in deep analysis of state-of-the-art technology, anticipating likely improvements while at the same time recognizing the technical limits of current and foreseeable technology at component and material level.

The platform concept has a number of unique properties which provide an attractive option for customers and users:

- The stack platform offers an attractive alternative to OEMs and several markets outside automotive and thus helps strengthen the supply side for OEMs and users.
- The stack specification represents a mature and comprehensive set of requirements reflecting the combined OEM, supplier and research expertise.
- High power density and scalability of the stack are providing full packaging flexibility for different OEM platforms and applications as well as different power requirements.
- The stack design offers the benefit of high performance at the lowest possible cost based on state-of-the-art technology. It thus can help achieve automotive target cost quicker.
- The inherent low cost approach of the automotive stack design can be conveyed to other applications while reducing the stack specific cost by at least one order of magnitude.
- The product concept is establishing a controlled risk approach with high probability for technical and market success while pushing state-of-the-art technology to its limits.

The 2015 launch date announced by several OEMs puts commercialization of fuel cell vehicles in reach. While this reflects the great technical advancements achieved over recent years, it will at the same time increase the pressure on competitive product cost to provide a sustainable and attractive choice to customers. Assessments based on business as usual suggest that the cumulative economic gap for commercializing FCEVs may accrue up to € 25 billion until 2020 due to the relatively higher cost of FCEVs vs. conventional vehicles. This might generate a financial gap of € 1 billion/year per OEM which will have to be subsidized.[6]

In this context, the fuel cell stack offers the largest cost reduction potential as it represents the major cost element of the fuel cell system. Thus, establishing platforms, combining volumes and sharing investment for stack development and production can establish a strong positive impact on improvement of economies of scale and save large amounts of money.

[6] “A portfolio of power-trains for Europe: a fact based analysis“, McKinsey & Company, Nov 2010, page 48f

The proposed platform design therefore offers a unique option and chance to facilitate the automotive business case during early commercialization phase, at least until 2025.

3.5.3 Compliance with other applications

The Auto-Stack specification was established to allow operation in vehicles but also in other applications. It is expected, that growing amounts of renewable power will create a market for peak shaving and intermittent power supply in the framework of a future smart grid in Europe. With the political objectives for introduction of renewable energy in Europe and the recent enforcement of these targets after the Fukushima accident, it appears that this scenario may become a reality even before 2020. UPS and back-up systems in such a scenario are assumed to deliver peak/intermittent power to the smart grid and thus ensure stability of energy supply under the new conditions of a sustainable energy system based on the use of renewable energy. Contribution of fuel cell backup power generators to peak shaving and intermittent power supply in the electric grid will further facilitate the business case for fuel cells in the power generation market.

Though favorable market conditions are likely to emerge, the fragmentation in PEM stack development in many cases prevents critical mass, disregards technical synergies and thus lacks technical and cost competitiveness. Commercialization of fuel cells in several of the stationary applications thus is often lacking momentum. Too little choices on the supply side in the 10 to 100 kW-class (only one major supplier for PEM-stacks) are another threat with regard to establishing a competitive market environment for system integrators and users/operators.

The Auto-Stack platform approach is striving to achieve step change in terms of performance, robustness and power density while addressing the application specific durability and degradation targets. The platform delivers a tool for massive cost reductions based on design to cost methods practiced in the automotive industry and substantial improvements of economies of scale by accumulating volumes of different applications. Initial analysis was therefore suggesting that there may be enormous benefit with conveying automotive stack properties to other applications. The key benefits are much higher power density combined with high performance and the inherent low cost approach of automotive design.

A comparison of typical specification parameters is displayed in Table 7 – below.

Current Stationary PEFC Stacks	Automotive PEFC Stacks
Moderate power density (~0.4 W/cm^2)	High power density (~ 1.0 W/cm^2)
Medium cell pitch (~ 5 mm)	Low cell pitch (<1.5 mm)
Endurance requirements: Continuous power generation: > 40,000 h Intermittent power generation: ~ 10,000 h UPS / backup power generation: ~ 4,000 h	Endurance requirements: … Heavy duty vehicles: > 10,000 h Light duty vehicles: > 5,000 h
Turn down ratio ~ 1:3	Turn down ratio ~ 1:20
Average single cell voltage: 550 – 800 mV	Average single cell voltage: 650 – 850 mV
Limited cycling capability (~3,700)	Full cycling capability (> 30000)

Table 7: High level technical comparison between Stationary and Automotive

Based on the high level comparison, a more detailed assessment of the technical compliance level was carried out. In this assessment, typical specification requirements of target applications were analyzed excluding applications with > 10 000 hours durability requirement.

As result of this analysis, the following applications were identified as complementing targets for the stack platform assuming operation with hydrogen:

- APUs for several purposes such as marine, rail and truck applications
- UPS- and back-up power for telecom, IT and other markets, including peak shaving and intermittent power
- Range extenders[7] for electric cars, buses, trucks and special vehicles
- Power generators for distributed and portable power.

Operation with other fuels than hydrogen may be considered. This will however depend from the fuel quality (i.e. reformate from hydrocarbons or alcohols). In the assessment, key specification parameters were analyzed and weighted. A rating was established and a threshold introduced as to how much compliance will be required to make it a realistic technical fit. The threshold was determined with at least 80% compliance. Some of the specification parameters such as durability had to be fulfilled 100% as they were considered to represent eliminating criteria with regard to technical compliance.

The compliance factors of individual applications with the Auto-Stack specification as determined by this assessment are displayed in
Figure 15 – below.

[7] Range extender in this context means fuel cell systems in hybridized vehicles operated with low dynamics either as a charging system to batteries or for direct propulsion in combination with batteries.

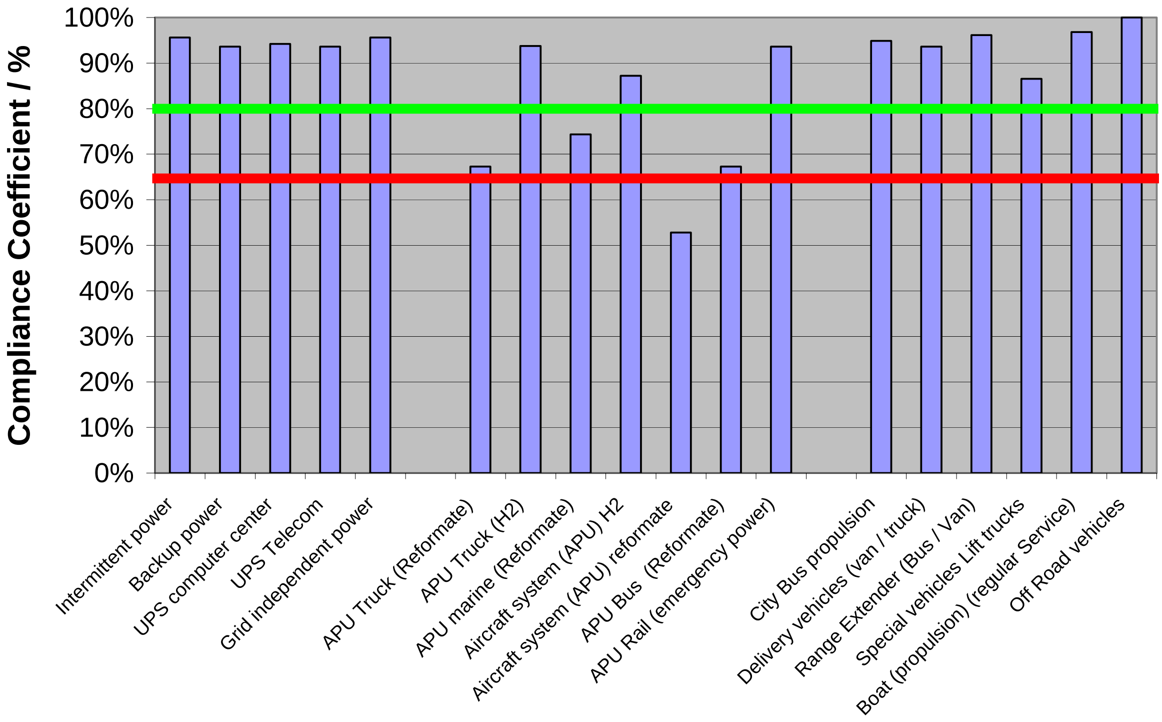


Figure 15: Compliance factors of other applications

3.5.4 Market Analysis

The anticipated market introduction scenarios for the automotive industry are very well analyzed and described.[8] Expected volumes for market introduction are:

- **100.000 FCEVs by 2015 and**
- **1.000.000 FCEVs by 2020.**

The total market volumes may be distributed amongst a growing number of OEMs participating in the commercialization of fuel cell vehicles. This is suggesting that production volumes of individual OEMs will stay below optimum production rates for quite a long time with all the negative economic consequences.

Several OEMs do not have technical solutions available and may be forced to either join alliances with more advanced partners or catch up on their own expense, both representing very costly exercises. Hence, there are many reasons for OEMs to have a closer look to the Auto-Stack platform concept as it addresses these specific challenges.

The analysis of potential market volumes for complementing applications identified a substantial additional volume potential. Even with a conservative approach, i.e. only assuming 10% of the total market potential of these applications as accessible, ten thousands of addi-

[8] A portfolio of power-trains for Europe: a fact based analysis", McKinsey & Company, Nov 2010, page 48f

tional units can be added providing additional revenues in the order of 1 billion € thus substantially facilitating economies of scale.
The detailed results of the market potential analysis are displayed in Figure 16 – below.

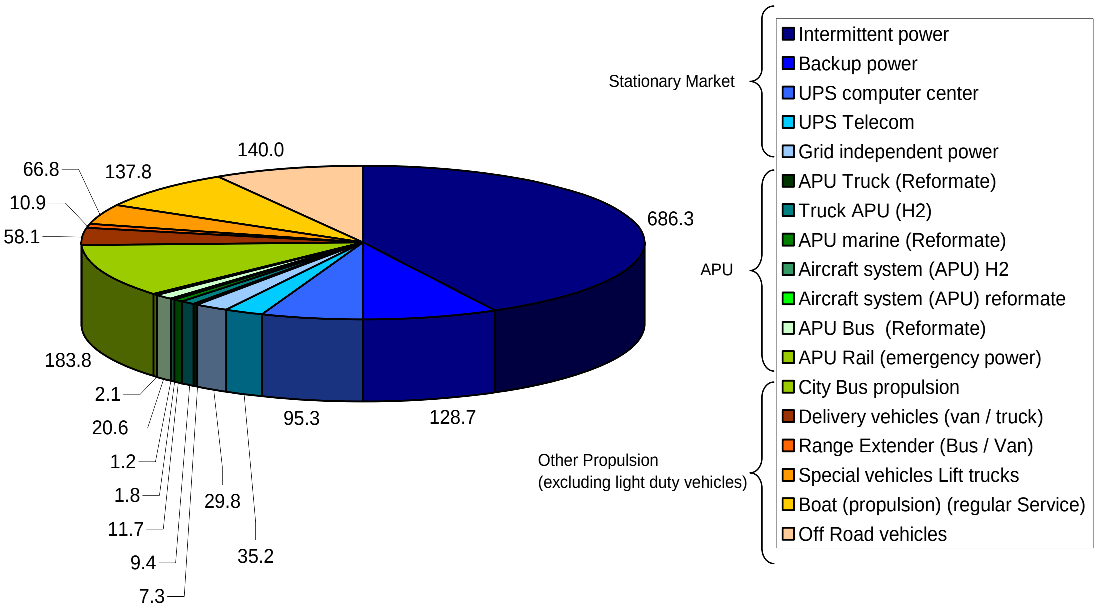


Figure 16: Market volumes of complementing applications (million €)

Today, the industrial supply side is more or less represented by one company (Ballard) only. European manufacturers such as Nedstack, Proton Motor, Intelligent Energy … yet have to prove their technical maturity and market success. But even then, they represent essentially niche suppliers with limited flexibility to successfully access larger markets due to the limitations of their product specification.

The sales revenues planned for the venture based on the market assessment are contained in Figure 18, section Financial Plan, below.

3.5.5 Organization

The proposed organization for the stack integrator suggests a lean organizational approach focusing on core competences. These core competences are representing all the functions needed to effectively execute product development and manufacturing of the fuel cell stack. They will be supplemented by support to core functions representing capabilities which are needed to effectively operate and manage the organization but are not essential part of product development or manufacturing. These functions are displayed in Table 8 below.

The organization is supposed to grow over time along with the requirements of different development phases and maturity levels. It will be subject to changes and adjustments as may be required to address the different needs of a growing organization. Due to the specific requirements of automotive industry, a strong context of automotive expertise will be required when filling key positions.

Based on these considerations, the following functions are considered necessary for the stack integrator:

Core competences	Support functions
Stack Development and Design (concept, interfaces, specification, IP)	Sales & Marketing
Component Specification and Validation (MEA, BPP, BoP)	Program- and Project Management
Stack Prototype Build, Testing and Validation	Infrastructure and IT
Supply Chain Management	Finance & Administration
Manufacturing/Assembly	
Quality System	

Table 8: Organizational functions of the stack integrator

The starting structure may consist of up to 25 staff and will include all functions needed for early development. The mature structure may grow to 45 staff depending from the final scope of activity and the associated resource needs. Preparation of mass production will post additional requirements for manufacturing, logistics, quality and support functions. This may require additional 10 – 15 people totaling staff to 65 (advanced structure, see Figure 17 below).

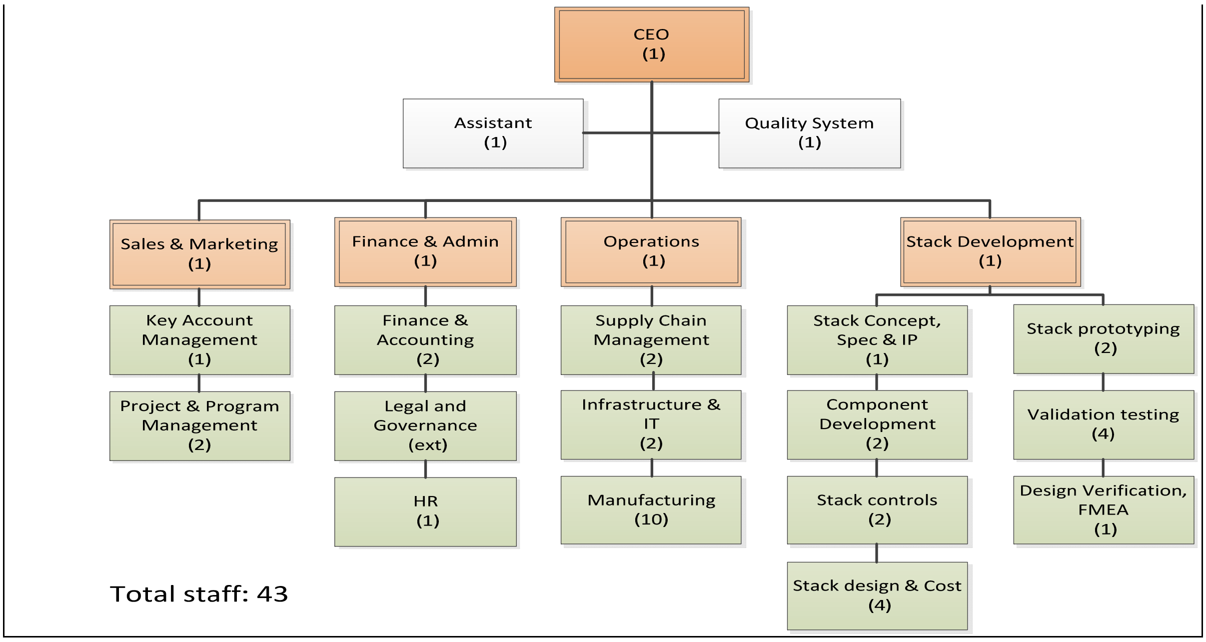
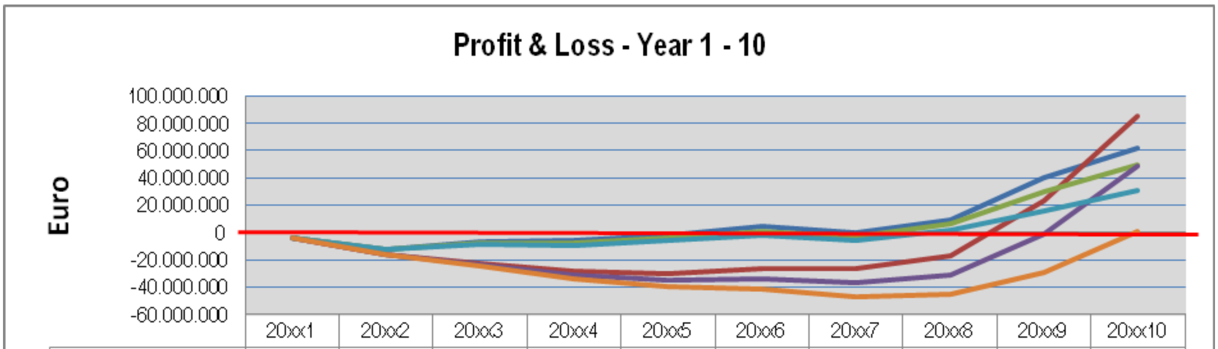


Figure 17: Proposed mature structure of the organization

3.5.6 Financial Plan – Profit & Loss

The financial planning for the business concept was established using the assumptions explained in the previous chapters and specific deliverables of the project. This does explicitly refer to the proposed organization and staff, assumed product cost and learning curves, investment needs and operational cost, sales revenues and profitability scenarios.

The assumed sales revenues are reflecting the product development cycle considering volume effects from other applications, i.e. with limited volumes for generation 1 (max 4000) and extended mass production volumes for generation 2. Starting from year 4 until year 9, sales to other markets may be as high as 50% of total sales. Hence, synergies with other applications will significantly facilitate the business case in early years. The share of these sales will however shrink and are assumed to level out to 5 – 10% when full automotive volumes will be achieved. The results of the detailed financial analysis are displayed in Figure 18 – below.



	20xx1	20xx2	20xx3	20xx4	20xx5	20xx6	20xx7	20xx8	20xx9	20xx10
Annual Result 1	-3.641.000	-12.092.50	-6.552.500	-5.629.000	-2.370.000	4.156.000	-230.000	9.109.000	40.648.000	61.774.000
NPV 1	-3.641.000	-15.733.50	-22.286.00	-27.915.00	-30.285.00	-26.129.00	-26.359.00	-17.250.00	23.398.000	85.172.000
Annual result 2	-3.641.000	-12.392.50	-7.552.500	-7.429.000	-3.970.000	1.156.000	-3.230.000	6.079.000	29.998.000	49.374.000
NPV 2	-3.641.000	-16.033.50	-23.586.00	-31.015.00	-34.985.00	-33.829.00	-37.059.00	-30.980.00	-982.000	48.392.000
Annual result 3	-3.641.000	-12.542.50	-8.552.500	-9.229.000	-5.570.000	-1.844.000	-6.230.000	2.039.000	15.798.000	30.774.000
NPV 3	-3.641.000	-16.183.00	-24.735.50	-33.964.50	-39.534.50	-41.378.50	-47.608.50	-45.569.50	-29.771.50	1.002.500
Unit sales / 100 kW	0	10	200	400	2.000	4.000	4.000	10.000	50.000	100.000

Figure 18: 10-year financial plan - profit and loss

In essence, the following conclusions can be drawn from the financial assessments:

- The venture will need 7 – 8 years until reaching breakeven. This is more or less independent from the assumed profitability but mainly determined by reaching a production volume of at least 10 000 units/year.
- There is a significant contribution of sales to other applications for achieving break-even and profitability of the venture.
- The total cash flow requirement will range from € 30.3 million (scenario 1) to € 47.6 million (scenario 3) strongly depending on profitability rather than volume.
- Return of investment will require 9 to 10 years as result of profitability combined with volume growth.
- The level of investment requires strategic, long-term oriented industrial investment with OEM support and strong commitment to the technology.

The assessment deals with stack development only and does not consider other elements such as system development and vehicle integration. These elements will easily increase the total investment needs to the 4-5-fold from the OEM perspective.

It is very obvious that these financial challenges can only be managed in the context of a strong business case. It is also critical to understand that these challenges are not only established by the direct investment needs of stack development but also by the sales subsidies required by OEMs prior to reaching optimum production rates and thus competitive stack cost. Isolated action will fail to utilize the technical and commercial benefits which can be delivered by a collaborative approach.

A simplified model delivered in Figure 19 illustrates the economic effects on product cost (sales subsidies) that can be saved by utilizing the proposed collaborative approach by Auto-Stack. The potential savings range from a few million Euro at low volumes to near to 200 million Euros at high but not yet optimum automotive production rates.

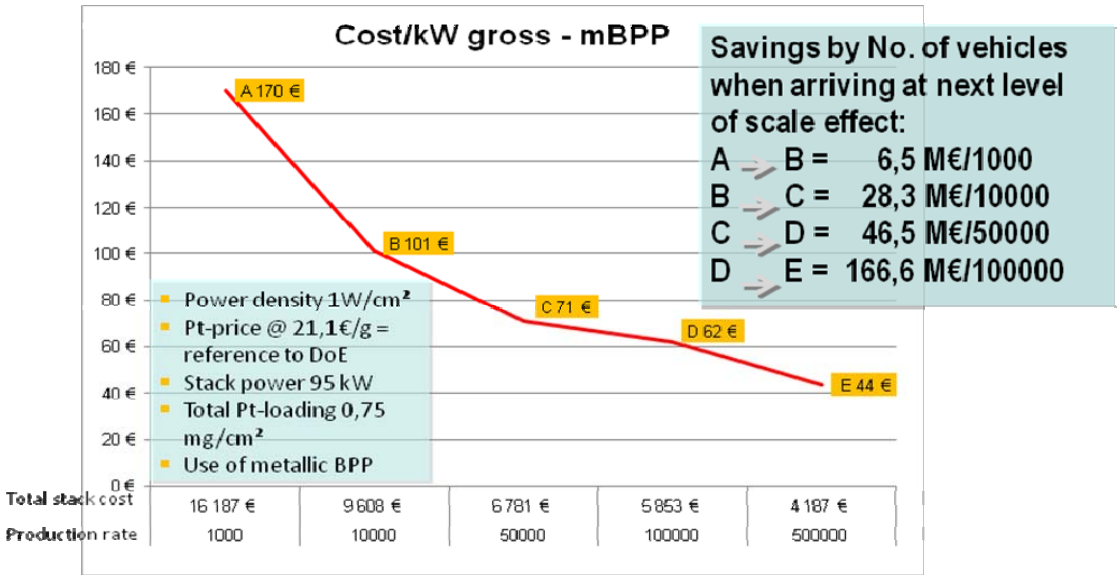


Figure 19: Economic effects of accumulated volumes on OEM subsidies

3.6 Potential Impact of the Project

Auto-Stack has demonstrated the benefit of collaboration between different stakeholders towards one common objective. It has not only delivered new insights to a number of technical aspects of stack development, but created visibility of the challenges towards achieving the technical and economic targets for fuel cell commercialization in automotive application. It has shaped the understanding of critical issues, facilitated communication and discussion about them and developed options and proposals how to address the associated issues. The results outline the benefits of a platform concept for the industrialization of automotive fuel cell technology.

3.6.1 Industrial Impact

The investment and financing requirements for automotive stack development establish a dimension of commitment by far exceeding typical engagements and the financial power of small and medium sized companies who are the typical supply chain players. This, combined with the existing commercialization risks for fuel cells and hydrogen, represent a level of risk exposure which only can be accepted with a strong strategic commitment to the technology, an excellent cash position and strong financial power. Regulatory pressure is needed as a key driver under any circumstance. Companies of this category, who combine all the three elements and are subject to emission regulation, are typically automotive OEMs or exceptionally very large global automotive system suppliers.

From the OEM perspective, stack development however establishes only a fraction of what is needed to develop a fuel cell propulsion system and for its integration in a specific vehicle. Based on industrial experience, the entire investment need is estimated 4 to 5 times higher and thus may establish a total commitment in the area of € 200 – 250 million. Though, these numbers seem huge, they are however not uncommon to automotive OEMs. The development of a new combustion engine for example does require similar financial commitments.

For the automotive industry, investment in fuel cell propulsion is therefore not a question of unprecedented financial engagement but a question of priorities. OEMs do or do not invest in the technology depending on their portfolio strategy. The level of OEM engagement is as diverse as the number of vehicle electrification and alternative propulsion concepts. The lack of strategic clarity poses significant uncertainties to the supply chain. Though several companies engage in fuel cell technology, they need to limit their risk exposure to acceptable limits as long as no consolidated roadmap is visible. The lack of strategic guidance and certainty thus establishes limits for investment and barriers for the development of a competitive supply industry. It is obvious that due to these factors, the overall technology development is slower than it could be, economics suffer by low volumes and long development cycles and overall strategic orientation is penalized.

In this context, Auto-Stack offers different levels of benefit to OEMs and the supply chain industry. The assessments and particularly the supply chain analysis made obvious that available technology for mid-term commercialization will require certain technical trade-offs to comply with the application specific technical and commercial targets. This regards particularly to Pt-loading levels which can be achieved. It was shown that high power density is the key technical objective as it delivers the best trade-off between performance and cost, addresses the limitations of current technology and allows a common platform concept for different OEMs and vehicles. Focus of initial commercialization activities therefore shall be put on scale effects to drive down the cost for OEMs and suppliers. The delivery on ultra-low Pt-loadings can only be achieved in the long term if advanced components will be available with the desired properties.

Thus it is proposed to shape current technology towards initial commercialization requirements first and work on breakthrough innovation with a more long-term timely perspective. Figure 20, next page, illustrates what is essentially a two phase strategy towards commercializing automotive fuel cells.

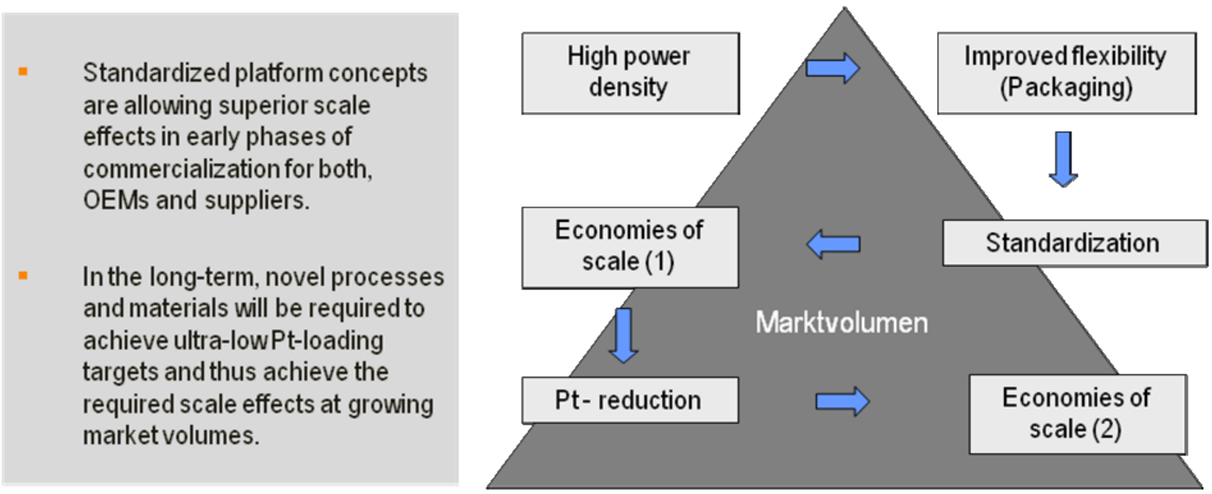


Figure 20: Proposed two phase commercialization approach

It was also shown that by selecting the proper technical concept, common stack platforms across several OEMs and fields of application are feasible and even more importantly are beneficial. The platform concept shapes the technical analysis towards choosing the proper technical objectives with the given technology. Synergies with other applications can substantially improve economies of scale during early commercialization and thus help enable the business case.

Accumulated volumes and transparent cooperation schemes are improving the business assumptions for the supply chain, help ensure the required investment and thus strengthen the development of a stronger and more diverse supply chain in Europe. The Auto-Stack platform therefore delivers an excellent tool to exploring a multitude of technical and economic synergies mitigating and substantially reducing the challenges and the cost of market introduction of automotive fuel cells in Europe.

The success of the current industrial attempt towards vehicle electrification will depend on the success of fuel cells as limitations of battery technology will not allow the required broad conversion of vehicle propulsion technology. Automotive stack development shall therefore be a central area of public support and investment in collaboration with the relevant stakeholders.

3.6.2 Technology and Research Needs

Communication between industry and research partners has substantially improved the mutual understanding, facilitated the recognition of the respective expertise and the value of cooperation when aligning towards one common objective. Auto-Stack thus delivers a template for a more comprehensive collaboration model between industry and research. The clarification, consolidation and alignment of technical objectives both in terms of their specification requirements and their timely sequence provides orientation and allows better focus of further research activities and the selection of research topics in the MAIP and the AIPs of the FCH JU as well as for other stakeholders. Specific proposals were submitted to the FCH JU and should be considered for implementation.

The consolidation of automotive OEM requirements establishes better visibility and shapes the research perspective towards potential technology options and their suitability to fulfill automotive specification requirements. The assessments have facilitated certain choices on operating conditions, stack architecture, bipolar plate materials and MEA performance which seem to establish best options towards achieving the technical and commercial targets with current technology. Orientation on power density in combination with high performance and durability establishes several challenges on components and materials which will need to be addressed by inherent material improvements and advanced components. Step change with regard to Pt-loading will require new alternative breakthrough solutions with regard to novel catalysts and/or catalyst materials and manufacturing processes. These shall be developed observing the challenges associated with efficiency, durability and cost in automotive application. Proper priority setting is therefore a key issue for better alignment of research activities with industry needs.

The research community has to play a key role to deliver the required innovative application oriented technology solutions. Given the current lack of industrial engagement in automotive stack development in Europe, the research players may have to play a critical role to mitigating the associated risks by driving the technology closer towards industrial readiness. Automotive stack development should therefore also be in the centre of activities of the FCH JU.

4 Main Dissemination Activities

Due to the nature of Auto-Stack, three different dissemination levels were determined, i.e. confidential, restricted and public information. This structure was chosen to ensure confidentiality of sensitive data or critical results, allow restricted dissemination on specific topics for the involvement of selected relevant stakeholders and public dissemination of broader project results. The dissemination activities were established and executed along these three categories.

The coordinator together with consortium members has carried out numerous dissemination activities in the course of the project amongst them:

- A project web-site was established. Consortium members and other interested stakeholders can access the project web-site for information.
- Four workshops have been held during the duration of the project involving stakeholders outside the project consortium:
    - November 17th 2010, stakeholder workshop, Ulm
    - February 7th 2011, stakeholder workshop on stack design options, Grenoble
    - February 8th 2011, public workshop on intermediate results, Grenoble
    - June 12th 2011, public workshop on stack design, cost model and resources requirement
- Individual presentations to European stakeholders such as
    - Nedstack,
    - Intelligent Energy,
    - Siemens,
    - Bosch,
    - PASM,
    - BMW and
    - Daimler were held in the first and second quarter 2011.
- Public presentations in conferences to a general audience were held at the following events
    - Supply chain workshop of NOW in Berlin, May 2011
    - Status Seminar of the German Department of Economy in Berlin, June 2011
    - The European Fuel Cell Forum in Lucerne, June 2011
    - EUCAR in Brussels, September 2011
    - The 2nd international workshop on degradation issues in fuel cells in Thessaloniki, September 2011
    - Fuel Cell Seminar in Orlando, FA, October 2011.
- The coordinator has presented intermediate project results during the FCH JU stakeholders general assembly 2010 as well as during review days in November 2011 and a presentation will be held by CEA during the European Fuel Cell Seminar in Rom, in December 2011.
- A number of publications are under preparation and will be released in coming months.

The proceedings of the public workshops are available from the project web-page (

Due to time constraints, a final public workshop could not be held ass planned during the duration of the project.

5 Exploitation of Results/Foreground

The results worked out during the project will be used by the consortium members in setting up their specific R&D plans. They will provide valuable input for subsequent product development as well as R&D proposals. and The cost model developed within the project will also provide further guidance in hardware development projects.

The project results have already been used as a basis to propose component and stack development projects during the FCH-JU AIP 2010 and 2011 calls for proposals by members of the consortium. Further R&D-proposals are in preparation.

6 List of Publications

No specific publications except conference abstracts have been released during the duration of the project. Different publications are under preparation in the preparation period of the report.

7 Plan for the Use and Dissemination of Foreground

The project results have been disseminated via the project web page, conference presentations and public workshops. Proceedings of the public workshops are available for download from the project web page. The project web It is intended to extract selected project results for publication in scientific and trade journals. Furthermore, the public summary reports of the project deliverables as well as the public final report will be available for download from the project web page. The project web page will remain active for a minimum of two years after the completion of the project.

8 Report on wider societal Implications

As was outlined in the previous sections, competition of different alternative propulsion concepts and OEM portfolio strategies establish a complex and confusing market context for stakeholders, including customers, operators, investors and governments. Exact prediction of market volumes and other quantitative considerations are very difficult. Qualitative analysis is required to identify the critical barriers and levers for market uptake.

Despite all technical achievements in vehicle emission reductions over past decades, the upward trend of emissions could not be stopped. The EU objective for overall CO2 – reductions by 80 – 95 % until 2050 will require a reduction of at least 60% in the transport sector.[9] It is obvious that fundamental changes of the transport system will be required to stop and reverse the existing trend. New alternative power trains are critical to address the challenges, comply with the emission reduction targets and uncouple transport from oil. In the overall energy context, nothing is required but changing the entire energy system.

It is obvious that this cannot be done by individual companies or sectors assuming free interaction of market forces. It is therefore necessary, that governments face the challenge, help establish joint common public - private strategies and establish market support mechanisms, including regulation, to facilitate the necessary changes. Assessments deliver the factual basis that fuel cells in transportation and other applications will have to play a central role for reversing CO2-trends and reducing environmental impact. Fuel cell stacks are a key component in this context and a strategic element of next generation propulsion products. It appears therefore, that Europe needs to face the challenge of supporting this development with even more emphasis than was done in the past to mitigate market failure and meet the demand of future automotive markets and the environmental objectives of the EU.

Current reluctance of most European OEMs establishes a strategic threat versus their Japanese, Korean or U.S. competitors. Europe is therefore running the dilemma that except for one company most of its automotive companies are late, may be too late, in the technology development. On top, the challenges associated with the development are underestimated and may thus only be recognized when markets have overhauled. This poses enormous risks for one of Europe's most important industries and its overall competitiveness.

Collaborative approaches as proposed by Auto-Stack can address the investment needs better, establish effective and straight forward development approaches and address the cost topic by alternative design concepts and improved economies of scale. Implementation of the required activities however will need public-private collaboration and will ultimately depend on the will of OEMs to cooperate.

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[9] Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system – White Paper – March 2011, p. 3

Consortium Members and Contacts

Organization	Contact Person	e-mail
Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg	Ludwig JÖRISSEN	Ludwig.joerissen@zsw-bw.de
Commisariat à l Energie Atomique et des Energies Alternatives	Thierry PRIEM	Thierry.priem@cea.fr
Daimler AG	Florian FINSTERWALDERr	Florian.finsterwalder@daimler.com
Reinz Dichtungs GmbH	Raimund STRÖBEL	Raimund.stroebel@dana.com
Centro Ricerche FIAT spA	Secondo SIBONA	Secondo.sibona@crf.it
Freudenberg FFCCT KG	Volker Banhardt	Volker.banhardt@freudenberg.de
JRC-ie	Georgios TSOTRIDIS	Georgios.tsotridis@jrc.nl
Paul Scherrer Institut	Felix BÜCHI	Felix.buechi@psi.ch
SNECMA SA	Fabien DJEEMA	fabien.boudjemaa@snecma.fr
SOLVAY SA	Nicola ZANDONA	Nicola.Zandona@solvay.com
Solvivore GmbH & CO KG	Markus Holzmann	markus.holzmann@solvicore.com
Umicore AG & CO KG	Ralf Zuber	ralf.zuber@eu.umicore.com
Powercell Sweden Ab	Per Ekdunge	Per.Ekdunge@powercell.se
Volkswagen AG	Benno Andreas-Schott	benno.andreas-schott@volkswagen.de
Associated consortium member		
Belenmos Clean Power	Uwe Hannessen	

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