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A Transition Management Roadmap for Fuel Cell Electric Vehicles (FCEVs)

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Abstract Fuel cell electric vehicles (FCEVs) have been considered as the future vision for the automotive industry. An increasing number of concepts and prototypes have been introduced in the last decade. In parallel with the technological development, recent discussions about global warming and climate change bring public support for emission free vehicles. Despite of the advancements and support, the speed of introduction of FCEVs is still not at the desirable levels. From a transition management perspective, the present paper seeks to answer the underlying factors behind the implementation of the FCEVs. The discussion goes beyond a technical one to cover broad factors and interests of stakeholders with an 'eagle-eye view'. Following a discussion the key drivers of change for the FCEV sector and wild cards with disruptive effects, the paper proposes a strategic roadmap template to set an agenda for a successful transition towards FCEVs.

Keywords Transition · Fuel cell · Electric vehicles · FCEV · Scanning · Roadmapping

Introduction

Transitions are defined as "transformation processes in which society changes in a fundamental way over a generation or more" (Rotmans et al., 2001). Transitions are the results of synergistic changes and developments in multiple domains, which reinforce each other. They require time and collective effort. A well-planned transition process includes a process of technological change, social and economic transformation, policy and legal re-organisation among the others, which take place at different levels of

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aggregation such as international, national, regional and corporate. The discussion in the present paper focuses on how to achieve transition towards fuel cell electric vehicles (FCEVs), which have been considered as a future vision for the automotive industry.

A transition of the transport sector, overall, towards greater sustainability and eco-efficiency is high on the political agenda of many governments (Schippl, 2016). Manufacturers in the industry have been working on concepts and prototypes for more than a decade now, while having advancements in addressing the main technical challenges like battery life. In parallel with the technological developments, recent discussions about global warming and climate change caused by carbon dioxide emissions brought public support for emission free vehicles, which are perceived as an asset. Despite of advancements and public support, the introduction of FCEVs is still not at the desirable levels. Car manufacturers frequently announce the near time launch of FCEVs, which are postponed with the same frequency.

Numerous business models and market projections have been made for the launch of FCEVs resulting in promising roadmaps. But it is obvious that these roadmaps reflected mainly the technology side while lacking a fully fledged consideration of the market side. The reason for this may be the fact that some of the actual and potential stakeholders are overlooked. Commonly, market roadmaps make assumptions of customers' behavior, take into account competing products etc. but neglect the more or less 'hidden' stakeholders, which become obvious if one analyses the systemic impact of FCEVs as innovations within industry value chains in relation to the transportation sector in a broader sense.

The present paper aims to make an attempt of a systemic analysis for a broader and more holistic view, which may portray the bigger picture, and help to understand the industrial dynamics better. The key argument is that the stakeholder base in the transportation industry, and in FCEVs in particular, is broader than usually thought. There are a number of other issues to be addressed for a successful and widespread launch of FCEVs. The roadmap presented in the study, entitled 'FCEV Global Market Creation', undertakes a broader analysis of Society, Technology, Economy, Environment and Politics (STEEP) at two stages. First, the STEEP systems are discussed and the stakeholders for each item are analysed. From this analysis, some potential barriers for the diffusion of FCEVs have become clearer. A more in-depth analysis may yield more insights for the implementation of the FCEVs.

Thus, the second section of the paper provides a background for the study and motivations and main issues for the transition into FCEVs. Approach and methodology used for analysis will be described in the third section. Following, a systematic and holistic analysis of external drivers and stakeholders will be presented in the fourth section to uncover broader set of issues affecting the FCEVs. The final section of the paper will present a roadmap template to bring together demand and supply dynamics and strategies to be adopted for successful FCEV implementation.

Background and Objectives

Climate change, increasing pressures on natural resources and environmental hazards are among the indications that humanity is reaching to the end of the reliance on non-renewable sources of energy like oil, coal and natural gas. The scramble is now on to find renewable energy sources that will keep cars, homes and businesses running without damaging the environment. Among the alternatives for future energy sources, hydrogen comes as one of the first options. It is an infinitely renewable and relatively pollution-free fuel that scientists, policy makers and society alike see as a viable alternative to fossil fuels.

In the automotive industry, hydrogen is a promising alternative for combustion engines. A hydrogen fuel cell in a car produces zero emissions with only water vapour and heat released through the tailpipe. Hydrogen is three times more efficient and provided that renewable sources are used for generation such as water and energy; it releases almost no emission. Hydrogen can be used to power vehicles as well as to be used in fuel cells to generate and store energy. Both of these technologies can be used separately or on the same platform, where a car can be powered by a hydrogen combustion engine and the fuel cell as a source of energy to supply electric power in place of a conventional alternator.

On the technical side, the main issues are related to the engine technology, and then to recovery, storage and transfer of hydrogen into the car itself. However, there is a broader range of social, technological, economic, environmental and political (STEEP) issues, which have positive and negative implications for the widespread implementation of hydrogen in the automotive industry. For instance, whether hydrogen and fuel cell technologies can be clean and efficient is very much dependant to how hydrogen is produced. Generation of hydrogen from oil and natural gas is much cheaper, but still puts pressures on natural resources. There are also struggles with storage and transportation under high pressure, which makes it bulky and impractical. As hydrogen has no smell, sensors must be used to detect leaks. In addition, a number of refuelling stations are required for hydrogen-powered cars. These are among the main barriers to the commercial development of hydrogen fuel cells.

The next few years appear to be critical for the commercialisation of the FCEVs. There are some promising trends. For instance, total worldwide fuel cell shipments grew 20% between 2014 and 2015, and 200% between 2011 and 2015 (US Department of Energy, 2015a & 2015b). Adequate refuelling infrastructure will be required for the FCEVs to be marketed as a credible and attractive alternative to conventional vehicles. Once hydrogen refuelling stations (HRSs) are available, the initial uptake of the FCEVs will be limited by the cost of buying and using the vehicles. The UK H_2 Mobility report (2013) predicts that sufficient early adopters should generate sales of approximately 10,000 vehicles per annum by 2020. As the vehicle costs become more competitive and refuelling network develops, FCEV uptake increases rapidly. The same report distinguishes three phases for implementing a viable business case for FCEVs:

1. Market seeding (2015–2020) with high capital costs and low number of stations—small at the beginning, but expandable in the future. Revenues are also low because of low number of FCEVs on roads. Stations are planned to the nearest places, where a critical mass of consumers exists—such as close to the feet bases.
2. Investing in growth (2020–2025). The number of FCEVs will grow. New stations will be built and the existing ones will be enlarged and upgraded. Revenues will increase gradually and HRSs will become more attractive.

3. Developed network and market (2025–2030). Demand is high enough to grow revenues and operations become profitable. A full network will be built by this time. Further HRSs will be built according to market demand.

No quick solutions are expected in the immediate future. At present, the total number of FCEVs has been estimated to increase by more than a factor of 10 from 2015 to 2020 and by a factor of 100 by 2030 (US Department of Energy, 2015a & 2015b). This is mainly due to a limited number of models on the market, limited infrastructure and higher costs compared to battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) (Global EV Outlook, 2013). First commercial introduction of FCEVs was in 2015 and more widespread HRSs are expected by 2020s. HRSs come to break-even in the late 2020s. By the 2030s, 20% of vehicles are expected to be FCEVs and by the 2050s 50%. However, successful demonstrations in Germany, Scandinavia, Japan and California indicate that there are great potentials for the deployment and use of FCEVs. Further countries are expected to make significant efforts to exploit the potentials and avoid risks associated to the STEEP dimensions of the FCEVs. The countries which will prosper will be the ones, which do not only develop technologies, but also implement them, develop necessary infrastructure, regulations and standards, as well as markets and promote them to a range of consumers for a widespread use. As all these require skills and capabilities beyond the technical ones, the present study adopts an “eagle eye” view with a thorough analysis of overall context and framework conditions as well as future technologies, which may shape the future of mobility and transport, and thus overhaul the automotive sector. The methodology used for the study is described in the next section.

Approach and Methodology

The process begins with a wider scanning and surveying phase (Miles et al. 2016), where the implications of key trends and drivers of change are examined with implications for the future FCEV markets. A typical scanning work involves an analysis of trends, drivers of change, weak signals, wild cards and discontinuities (Saritas and Miles, 2012). Thus, the exercise aims to fulfil both alerting and creative functions. The alerting function helps policy and strategy makers to anticipate emerging issues for transition, while the creative function explores new and emerging opportunities and issues (Amanatidou et al., 2012). In this respect, scanning looks for things that might change the situation, or change the way in which it is developing (Miles and Saritas, 2012). A framework based on the analysis of social, technological, economic, environmental and political (STEEP) systems was used to ensure that the topic is explored from multiple different, but also interconnected lenses. The analysis was conducted at two steps:

1. Identification of ‘external drivers’ through the analysis of societal, technological, economic, environmental and political determinants of FCEVs
2. Analysis and mapping of stakeholders to identify key players in each STEEP category

The external drivers (STEEP) are described in brief with emerging key issues under each of them. Following a basic outline of these sub items, Wild Cards (Saritas and Smith, 2011) are suggested for each category to describe those events and developments with a small likelihood of occurrence, but with big potential impacts on FCEVs. Three to four exemplary Wild Cards are presented under each category to provoke positive or negative disruptive thinking in the FCEV domain.

Next, the main stakeholders are analysed. The stakeholder analysis will help to bring both technical and non-technical dimensions of the topic, along with the values and preferences of the stakeholders (Saritas et al., 2013). Thus, each stakeholder will be discussed with their potential to influence the diffusion and absorption of the FCEVs as well as potential lines of argumentation against the transition to FCEVs. At the current stage, this analysis is not exhaustive and the stakeholders are listed in general terms with no direct association to a specific country or market.

The paper is concluded with a template of a roadmap for FCEVs. Roadmaps can be considered as "an extended look at the future of a chosen field of enquiry composed from the collective knowledge and imagination of the brightest drivers of change" (Galvin, 1998, p.803). Roadmaps may be constructed purely for technology, strategy or combination of different purposes. The template provided within the present study aims at suggesting a structure for developing multi-level and multi-dimensional strategic roadmaps. Saritas and Aylen (2010) and Aydogdu et al. (2017) present examples of strategic roadmaps in clean production and defence industries, respectively. The roadmap template provided at the end of the present paper is expected to be filled by the policy and strategy makers promoting the development of the FCEV technologies. As there is no available one-strategy-fits-all solution, different responses may be observed for the same trends (Thomas, 2015). Strategies may depend on very much the context they are implemented in and different perspectives and positions of stakeholders. How to develop context dependent strategies are described by Pettigrew (1987) and demonstrated with a Foresight exercise by Saritas et al. (2007). A proper technology intelligence analysis should be undertaken to examine the key elements of technological change and understand its broader implications (Ranjbar and Tavakoli, 2015). The originality of the present study lies in the fact that it brings together diverse range of issues affecting the FCEVs from a transition perspective.

Characteristics of External Drivers

Social Factors

Social factors involve the ways of life (e.g. attitudes to work time, use of leisure time, family living patterns, work-life balance), demographic structures, social inclusion and cohesion issues (fragmentation of lifestyles, levels of (in)equality, educational trends). Public attitude towards hydrogen is considered to be one of the key factors towards the transition to FCEVs. The social perception of FCEVs can be assessed in terms of the following:

- availability of a critical mass of customers

- accessibility to infrastructure
- aesthetics and convenience for making the vehicles attractive for the customers without compromising from quality

Availability

Building a critical mass of FCEV customers is a must for making the technology economically viable. For customers, initial purchase cost is one of the determinants of the selection of a vehicle. Without intervention or dedicated mechanisms, in the early years after market introduction, the FCEVs will be significantly more expensive than the conventional vehicles and re-fuelling will be limited with a low number of locations. These seem to be main barriers by the consumers. However, there are various ways of overcoming these initial barriers, which will be discussed in the Technology and Economy sections below.

Accessibility

The accessibility to infrastructure is obviously raised as one of the key points for the widespread use of FCEVs. Gas stations need to invest in the ability to refuel hydrogen tanks before the FCEVs become practical. Consumers require both local availability and national coverage for long distance travels. Detailed spatial modelling studies can be done to identify those locations to deliver the greatest consumer benefit. The low number of customers will make it less likely for such investments at the early phase; however, after providing sufficient initial coverage, then the network could be developed in line with the demand by the vehicle owners/users. Accessibility should also be considered in terms of availability of the maintenance infrastructure and associated repair frequencies and costs.

Aesthetics and Convenience

Customers increasingly value new technologies, environmental friendliness and costs of a new car. Performance and driving behaviour of vehicles are also considered to be important when purchasing decisions are made. The dependency between total costs and the availability of hydrogen refuelling stations (HRSs) are the key determinants of buying a FCEV. A recent survey indicated that some 10% of new vehicle buyers showed themselves to be potential early adopters of FCEVs, being receptive to new technology and environmentally motivated (UK H_2 Mobility 2013). The expectation is that the cars may cost higher to purchase at the beginning. However, when life-time costs are considered, it can be said that the operating costs will be considerably lower compared to existing internal combustion engines.

Various advantages of using FCEVs can be emphasised in the process of market creation, such as the following:

- Longer driving range as the electricity is generated in the car
- Hydrogen charging time is usually quick
- Like other electrical engines, there is no engine noise in the car—though, special effects can be created for motor fans

- No carbon dioxide is pumped into the atmosphere, no noise is made and the engine delivers better torque than most petrol cars, which translates to greater acceleration.

Considering all these factors, consumers appear to be receptive to FCEVs, especially in terms of vehicle performance and refuelling time. In the first 5 to 8 years of deployment, plug-in hybrid vehicles might be preferred given the fact that it is possible to use the existing petrol, diesel and electricity networks. However, as the HRSs expand, the advantage of longer driving range and quick refuelling time will be more attractive for car owners/users.

The UK H_2 Mobility (2013) report identified seven distinct consumer groups with defining characteristics under three categories as illustrated in the Fig. 1.

Being the 10% of the overall consumers, potential early adopters can be considered as the first target group. This group is willing to pay a premium prize for an FCEV. This makes the introduction of the FCEVs possible before cost parity is reached with existing vehicle technologies. The other groups would still require a discount to buy an FCEV.

Wild Card Thinking

Some Wild Card thinking can be applied for the acceleration of the speed of adoption of FCEVs:

- Strategies for attracting emerging young 'technology-savvy society' would be a good group to target to expand the potential early adopter group
- FCEVs can be presented with a new image by combining sleek design and technology, which may be used to create a new fashion. A number of people are ready to pay several times higher for an Apple iPhone than other phone models, similarly they may be ready to pay 1.2 times higher for a stylish car

	Potential early adopters		Probable late adopters		Technology followers		
Segment	**1** Well-off enthusiasts	**2** Innovative greens	**3** High mileage luxury	**4** Cautious pragmatists	**5** Single car value	**6** Younger sceptics	**7** Uninterested rejecters
Attitudes to infrastructure	• High willingness to drive to find H2 • Medium concern over 1 HRS per city	• Strongest willingness to sacrifice convenience	• Below average willingness to drive to HRS • Strong concern over 1 HRS	• Medium willingness to drive to HRS	• Limited willingness to sacrifice convenience	• Limited willingness to sacrifice convenience	• Will only drive short distance to find H2
Technology attitudes	• Strong tech enthusiasts • Willingness to pay for new tech	Wants and might pay for new tech	• Low innovativeness • Well informed on car tech	• Not interested in new tech	• Very low interest in tech • Low innovativeness	• Low interest in new tech	• Low interest in tech
Green attitudes	• WTO for green • Tad pipe more important than WTW	• Strongest green attitude • Green hydrogen important	• Weak green motivation • Not willing to pay	• Slightly green but no sacrifices	• Some concern about pollution but not WTP for green cars	• Some concern about pollution but not WTP	• Lowest environmental concern
Cost sensitivity	• Payback not important • WTP for green and new tech	• Payback more important for new/green tech	• Low running costs important • No WTP for green/new tech		• Low running costs important • Value buyer	• No WTP for green/new tech	• No WTP for green/new tech • Capital cost primary factor
Proportion in sample	-10%		-40%		-50%		

Fig. 1 FCEV consumer segments. Source: UK H_2 Mobility Report (2013)

- Recently, communications, electronics and photography sectors have converged to a large extent. It is expected that the automotive industry too will converge with those sectors. Integration and inter-operability with information, communication, multi-media systems and social networking technologies with large touch screens will also attract a number of users
- Mass media can be used to promote the FCEVs. Media attitudes are equally important, especially mass media which has strong impact on public opinions. It has been frequently observed that media tends to report on accidents and failures of technologies most preferably instead of success stories. Here, the impact of different media channels on consumer attitudes and behaviour could be given special attention
- Society should be convinced about the safety, security and reliability of FCEVs, without any negative impacts on public and individual health

Technological Factors

Technological factors focus on rates of technological progress, pace of diffusion of innovations, problems and risks associated with technology such as security and health problems. Some of the technological factors associated to FCEVs are as follows:

- Reliability of supply
- Equipment (hardware)
- Vehicle technologies

Reliability of Supply

The supply of hydrogen is an important issue for the creation of FCEV markets. Necessary infrastructure should be established to ensure sound and stable supply of energy. Any lack of supply can be easily used as an argument against FCEVs.

When hydrogen is supplied, environmental implications should also be considered. Pure hydrogen can be industrially derived, but it takes energy. If that energy does not come from renewable sources, then fuel-cell cars are not considered to be as clean as they seem. Ways should be found to generate hydrogen using renewable energy sources or integrated with carbon capture and storage (CCS) technologies.

Fuel storage and transport challenges seem to be solved at least technologically in principle. However, there still remain concerns with respect to logistical issues, e.g. centralised or decentralised fuel production, infrastructure for fuel distribution, the appropriateness of the existing infrastructure for upgrading to the respective fuel distribution.

Equipment (Hardware)

The cost of buying and installing equipment for compressing, storing and dispensing hydrogen on site and the cost of financing the expenditure should be considered at this point. A hydrogen refuelling station (HRS) is considered to have a 20-year life time. The cost of land should also be factored in the cost calculations. Operation of the equipment and facilities will incur certain costs too such as the cost of maintaining the

HRS, general operating cost, the cost of administration and sales and rental charge for the land used by the HRS—if it is not a mobile one.

Network development can be achieved with a number of small but widespread HRSs, which should be expandable with upgrades to medium- and large-scale HRSs. This option for expansion should be considered right from the beginning.

Vehicles

The vehicle technology is probably the most advanced and least problematic part of the overall FCEV business plans. A number of vehicle producers are ready for mass commercial production. Although FCEVs are more expensive than the cars with conventional engines at the moment, these costs are expected to go down following the “market seeding” phase between 2015 and 2020, when investments are made for growth, and networks and markets are developed.

An important issue here may be the maintenance and repair infrastructure for FCEVs. As FCEVs are equipped with more sophisticated technologies, special attention will need to be given to repair facilities and equipment, which may look quite different than current garages for conventional vehicles. The transport and storage of hydrogen and spare electronic equipment will need special attention in terms of security and safety. Operating staff training for this new technology should also be taken into account.

Wild Card Thinking

Possible technology related Wild Cards:

- New ways of extracting hydrogen. A team of Virginia Tech researchers has discovered a way to extract large quantities of hydrogen from any plant, a breakthrough that has the potential to bring a low-cost, environmentally friendly fuel source to the world.[1]
- Mobile hydrogen refilling stations can be used to provide further access to hydrogen in remote or congested areas, or when a likely power cut starts effecting supply. Powertech company has pioneered the use of lightweight carbon fibre composite tanks for the high pressure bulk transportation of hydrogen, for mobile hydrogen fuelling station applications and for portable self-contained hydrogen fuelling units. Transportable compressed hydrogen units can be custom-designed to meet customer needs, including transport trailers, mobile fuellers and portable filling stations.
- If the technology for BEVs does not develop significantly, and if the process of producing hydrogen becomes easier and cheaper, then the case will be much stronger for FCEVs.

Economic Factors

Levels and distribution of economic growth, industrial structures, competition and competitiveness, markets and financial issues are the sorts of factors to be considered

[1] https://vtnews.vt.edu/articles/2015/04/040715-cals-hydrogen.html (Last accessed on February 17, 2017)

under this category. As one of the key drivers for hydrogen cars, economic factors in this domain involve a number of points to be considered, including the following:

- Cost of FCEVs
- Demand
- Investments

Cost

Fuel cells (FCs) are still very expensive, even when compared to BEVs. FCs still remain to be 10 times more expensive than internal combustion engines; however, progress is made towards cost reduction. Another important aspect is hydrogen itself. Currently, there is no market price for hydrogen intended for alternative energy use comparable to that for gasoline. Hydrogen as an alternate energy carrier is in an early phase of development. Estimates of the cost of hydrogen per gallon of gas equivalent range from $2.10 to $10. Hydrogen produced from natural gas, the cheapest available method, is three to four times as expensive as gasoline, in terms of equivalent amounts of energy (US Department of Energy, 2015a).

The Department of Energy in the USA aims to reduce the cost of hydrogen to $2 per gasoline gallon equivalents by 2020 (US Department of Energy, 2015a & 2015b). Its previous goal of $1.50, set before gasoline prices went up, was based on the use of natural gas as a source for hydrogen. The new goal is independent of the method of production, in response to questions about the environmental effects of using natural gas for hydrogen production.

Demand

Overall, the market demand has three determinants:

1. Vehicle attributes including the price of the vehicle, performance and range and hydrogen consumption
2. Consumer attitudes in terms of different user segments presented above (Fig. 1) and the size of each group
3. Hydrogen refilling stations with a widespread urban and national coverage, hydrogen process and emissions generated through the production process

Economic feasibility means a target of 200 people per pump at the annual depreciation target of 250 Euro/year per customer to achieve the cost target of 500 K Euros over 10-year period (Hasegava, 2013). This may be challenging in the first period between 2015 and 2020, but then will gradually become more realistic.

Considering the cost and demand factors, first and immediate clients for the FCEVs seem to be fleets, such as bus fleets in Europe. Large number of vehicles may create the economies of scale that justify the cost of building stations. Among the expectations of the fleet operators from the FCEVs are low emission, long range and fast fuelling vehicles. Van type of vehicles is more preferred by this group. Special rates or tax exemptions are expected for low or zero emission vehicles. Fleets are also desirable to begin with as they have more predictable driving patterns than other users. Filling stations might be located at the fleet base or close to it.

Investments

Venture capital and private equity investments in fuel cells and hydrogen increased worldwide by 9.2% between 2014 and 2015. Venture capital and private equity investments in US fuel cell companies grew by 96.2% during the same period (US Department of Energy, 2015b). Coupling with the increasing investments, the FCEV industry may create further employment across the value chain from vehicle manufacture, development of new components, fuel production, distribution and supply, thereby bringing significant economic benefit.

The HRSs may not be profitable at the beginning. A break-even point may be expected in the late 2020s. Business cases should be created for the initial network of stations to ensure how first mover commercial advantage could be secured.

Wild Card Thinking

Possible Wild Cards in this category may include the following:

- The nearest-term application for FCs seems to be lift trucks (forklifts). Several industrial truck companies have announced commercial FC products that can replace battery-powered forklifts. These have been extensively tested and are available for commercial purchase today to be used in production plants, logistics and airports.
- A possible "electron economy" may replace the "hydrogen economy". In an electron economy, most energy would be distributed with highest efficiency by electricity and the shortest route in an existing infrastructure could be taken. The efficiency of an electron economy is not affected by any wasteful conversions from physical to chemical and from chemical to physical energy. With an electron economy, attentions could be quickly turned to the energy storage technologies and upgrade to smart grids.
- On the more positive side, UK-based AFC Energy is confident it has identified a low-cost and sustainable source of hydrogen in the form of the waste gases produced by the chlorine industry, and following successful trials at a chlor-alkali plant at Bitterfeld in Germany, the company is now working on a 50-kW commercial-scale version of its fuel cell technology. It should be considered that technology and economy should go hand in hand to achieve hydrogen breakthrough.

Environmental Factors

Pressures connected with sustainability and climate change and more localised environmental issues (including pollution, resource depletion, associated biodiversity and welfare concerns) are among the environmental factors to be considered. Environmental impact is one of the key arguments for supporting or contesting the transition process towards hydrogen powered FC cars. There are two key factors to be considered:

- Emission reductions, which is highly desirable
- Hydrogen production, which is frequently used as a counter-argument to the hydrogen economy

Emission Reductions

The environmental benefits of hydrogen are a very positive attribute. When used in a fuel cell to power an electric vehicle, the emissions include only water and heat. But hydrogen is produced using energy from natural gas, coal, solar, wind or nuclear power, each of which has its own environmental effects. The UK H_2 roadmap indicates that hydrogen production mix in the roadmap for 2030 is 51% water electrolysis (WE), 47% steam methane reforming (SMR) and 2% existing capacities. WE, using renewable electricity, includes both on-site production at the HRS and centralised production with distribution to the HRS. In 2030, the roadmap shows that the UK national demand for hydrogen for FCEVs will be 254,000 t p.a. FCEVs will help to meet long-term emission reduction targets by offering a practical mass-market solution to help meet this objective.

Hydrogen Production

Transitional approaches relying on natural gas could facilitate the use of hydrogen technologies until production methods using other, more environmentally friendly resources become available. Therefore, one likely early path for the development of hydrogen could be using the wide availability of natural gas and its distribution pipelines to create hydrogen for on-site fuelling.

Hydrogen can also be produced from coal reserves. Most analyses show that the higher efficiency of hydrogen applications can result in lower greenhouse gas emissions, even when the hydrogen is produced from coal.

Other environmental benefits of FCEVs include improved air quality and reduction in noise pollution from traffic compared with conventional vehicles powered by conventional engines. These can be used as additional arguments to promote FCEVs.

Wild Card Thinking

Some of the associated Wild Cards from the environmental point of view may include the following:

- Hydrogen is widely accepted as a solution to global warming by the UN with a decree.
- A breakthrough in electric power storage occurs within a decade involving battery technology, fuel cells, new chemicals and materials with some nano-technology applications. This breakthrough allows the integration of power systems in mobile equipment (cars and trucks) with stationary energy needs (back-up power and load

management option for homes, offices and factories). These storage applications begin in the high cost and high value parts of the energy sector and as the technology matures, costs decline and zero-emission targets become closer to achieve.
- High corn prices driven by a bad harvest could hurt corn ethanol producers, which are suffering from a saturated market for ethanol. This may allow hydrogen to take off faster than expected as an alternative energy source.

Political Factors

Political factors involve dominant political viewpoints or parties, political (in)stability, regulatory roles and actions of governments, political action and lobbying by non-state actors (e.g. pressure groups, paramilitaries). Regarding the hydrogen field, the following political factors can be considered to be influential:

- Reduction in energy dependency
- Political incentives
- Joint action

Energy Dependency

The commercialisation of FCEVs and hydrogen has potential benefits in terms of reduction of carbon emissions, air quality improvements and energy security enhancements, in addition to wider economic benefits. For instance, switching from imported fossil fuels to hydrogen may bring £1.3 billion annual benefit to the UK economy by 2030. Energy cost reduction potential for the transport sector in the Japanese economy was estimated to be 23 Billion Euros for 2010 (Hasegava, 2013).

Diversification of energy supply through hydrogen could help to reduce the reliance of imported fossil fuels for transport and thereby increase energy security in energy importing countries. The local production of hydrogen can also provide more of the process inputs to be produced locally by reducing the dependency on external energy markets.

Political Incentives

There are currently no production incentives for hydrogen. The political support often is limited to discussion about emission free vehicles but practical initiatives are missing. Limited public funds are available for research and demonstration projects.

As far as the cost of hydrogen is considered, a national pricing system will need to be introduced within countries. This will depend on the size of the country; distribution of hydrogen production facilities across the country and proximity to HRSs.

Tax exemptions are planned for hydrogen vehicles. However, the practical implementation of such tax exemptions might carry the danger of giving advantages to national or local manufacturers as was discussed after the crisis in 2008 when most European countries implemented such measures. Hence, national (country specific) measures have to be analysed in detail if these are applicable for fuel cell powered cars.

Joint Action

In order to overcome the commercialisation challenge, a close cooperation is needed between vehicle manufacturers; equipment manufacturers in production of fuel cells, hydrogen refuelling stations and hydrogen technology components and sub-systems; fuel retailers; hydrogen producers; energy utilities; and the government departments such as science, technology and innovation, transport and energy.

Wild Card Thinking

Some of the Wild Cards in the political sphere might include the following:

- Introduction of large-scale public procurement programmes for FCEVs
- Governments back zero-interest mortgage plans for hydrogen cars
- Massive movement of public transport vehicles and large fleets to FCEVs

Characteristics of Stakeholders

A number of roadmaps have been developed in course of the FCEV history. Although most of them were developed professionally, they still lack an 'eagle eye view' on the 'hidden' stakeholders' attitudes, influence and argumentation lines. Developing effective roadmaps hence requires knowledge and information about actual but also potential stakeholders, which follow their own strategies and might have the potential to block technologies and innovation diffusion or at least create obstacle and barriers to delay diffusion. It is important to underline that stakeholders vary in their influence on the diffusion of innovation, their power and their argumentation strategies. Bottom-up and top-down processes need to be considered together to foster sustainability (Hyytinen and Toivonen, 2015) and implement associate technologies like FCEVs.

Stakeholders—Societal

In the societal sphere, mainly customers are considered as stakeholders. However, they show special characteristics, in particular with reference to FCEVs. In the transportation business car, owners' associations also play an important role.

Stakeholders	Influence	Power	Argumentation strategies
• Traditional car owners	↗	↗	• Misses typical car features • Reluctant towards noiseless drive
• Young generation	↑	→	• Wish to differentiate from traditional drivers • Limited experience with infrastructure
• Car owners associations	↑	↑	• Adverse attitudes, mainly dominated by traditional drivers • Point on noise, danger of fuel supply, need to train traditional driver to adjust

→ low, ↗ medium, ↑ high

Overall, the individual stakeholders have only moderate influence on innovation diffusion, but associations representing car owners have considerable power at different levels.

Stakeholders—Technological

From the technological point of view, various stakeholders exist in the FC landscape. These refer to direct competitors, who aim at similar application but using competing technological solutions and surrounding actors like infrastructure suppliers and fuel producers.

Stakeholders	Influence	Power	Argumentation strategies
• Alternative FC (SOFC, PAFC, MCFC) producers	→	↗	• Similar application fields for FCs or at least potentially similar fields • Might point to dangers and environmental issues of membranes
• Infrastructure suppliers	↑	↑	• Decentralised infrastructures need to be build–investment cost • Existing infrastructure reshaped for fuel transport–opportunity cost
• Fuel producers (gasoline)	↗	↑	• Consequences of lacking demand for gasoline–refinery closures, job losses, impact on petrochemical industry

→ low, ↗ medium, ↑ high

The analysis shows that competing technological solution providers have potentially stronger influence on the diffusion of innovation. The reason lies in their technology follower position in the FC development, polymer electrolyte membrane fuel cells (PEMFCs) have been the main FC type for transport applications for a while but still other FC types might be used for mobile applications. Producers of these FCs might follow a strategy to point strongly on the inherent dangers of membrane technology, which are still manifold. Infrastructure suppliers have strong influence and power on the diffusion per se. As long as the infrastructure for fuel supply remains insufficiently developed, these actors need careful consideration and treatment. Other often neglected stakeholders are traditional fuel producers, who belong to downstream oil and gas business, eventually forming part of the petrochemical industry. Here, the challenge is that the fuel is commonly produced in refineries from crude oil using different cracking technologies—fuel is only one product of cracking crudes. So far, the essentials for the chemical industry are produced together with traditional fuel, there is no either or. It follows that with a significant reduction of fuel demand refineries need to lower output with respective impact on the subsequent industries. This gives reasonable arguments for the industry to block FCEVs.

Stakeholders—Economic

The most progressed FCEV producers are Asia-based companies. National producers in the Western markets are still lagging behind in technological terms; thus, they will aim at influencing the national, regional and local communities. In a similar way, the petrochemical industry will act (see also technological stakeholders). Last but not least, the repair and maintenance infrastructure lobby is important. Currently, any car can be fixed in emergency cases within the existing infrastructure but there remains a challenge to:

(1) upgrade the existing infrastructure on a broader scale for regular maintenance and
(2) to upgrade the emergency relief infrastructure.

Stakeholders	Influence	Power	Argumentation strategies
• Technology follower	↗	↗	• Technological leadership concentrated in Asia (Japan, South Korea), Europeans lagging, oppose with lobby work
• Petrochemical industry	↑	↑	• Job losses due to either refinery closure or high investment for new equipment
• Repair and maintenance industry	↗	↗	• Significant investment in equipment • No competences in new technologies, reluctant to accept dual system

→ low, ↗ medium, ↑ high.

Presumably, the strongest opposition might come from the petrochemical industry, which is well aware of the investments needed in their refining facilities to compensate for the decreasing demand in gasoline and related products. The repair and maintenance industry will need physical investment in line with extensive training to assure adequate services to customers.

Stakeholders—Environmental

In technological terms, FCEVs are not new at the small-scale production and operation. However, environmental groups and also health and safety-related interest groups might raise concerns about the reliability of manufacturing and operation of FCs in the broadest sense at large scale.

Stakeholders	Influence	Power	Argumentation strategies
• Laws, legal regulations	↑	↑	• Especially important for EHS
• Environmental groups	↗	↗	• Long-term H2 impact not known
• Health, safety groups	↑	↑	• Unknown reliability of new standards and technologies, potential negative impact on safety and health of workers in all domains

→ low, ↗ medium, ↑ high.

It can be assumed that the concerns regarding Environmental Health and Safety (EHS) will not be announced and communicated by the interest groups to the end user directly; presumably, the end user is not aware and interested in the manufacturing and handling of large-scale FC production units. Thus, these interest groups are likely to influence the policy level to issue related regulations and probably laws which might have reasonable impact on the business models. Also, there is a possibility that EHS-related arguments and interest groups are used by other parties with the aim of delaying FC diffusion.

Stakeholders—Political

The mass introduction but also the pilot introduction of FCEVs will require physical infrastructural adjustments of the public transport system. Also, there is a need at the policy level to implement complementary systems, for instance, by enforcing standards.

Stakeholder	Influence	Power	Argumentation strategies
• Municipalities	↑	↑	• Responsible for infrastructural decisions
• Regional	↑	↑	• Financial incentives for municipalities, regional standards, complementarities of standards between regions
• Federal	↗	↗	• Initiator and promoter role but less implementation power

→ low, ↗ medium, ↑ high

The main policy actors will be at the level of municipalities and regions. National level policy makers will have reasonable influence to design measures, which are supportive to FCEVs diffusion, still the implementation of any federal measures is at the regional and the municipalities' level. Especially, municipalities have the responsibility for assigning and licencing respective space for related infrastructure, whereas regional authorities will be responsible for monitoring and quality/safety testing and certification.

Development of an Eagle Eye FCEV Roadmap

A roadmap for the creation of a market for FCEVs is a tool for long-term complex planning, which allows setting strategic goals and estimating potential contribution of new technologies, products and services to build a competitive and sustainable FCEV market. The roadmap considers alternative ways to achieve the goals and choose the most efficient products and relevant technology applications. It provides decision makers with estimates of future markets and prospects of innovative products and design an innovative technological value chain from R&D to market entry. The FCEV roadmap presents estimated indicators of economic efficiency of the potentially prospective technologies and products, with the high demand potential and attractive consumer properties of FCEVs within the time scale also taking into account the elaborated stakeholder views. The proposed roadmap will be developed on the bases of both qualitative and quantitative methods, the expert community survey data and evidence-based analyses. In this stage, the stakeholder analysis will be incorporated in the market dimension of the roadmap.

The roadmap template presented here is designed on the basis of a market-driven and technology-driven approach, which starts from the analysis of a market demand. The elaboration of the FCEV roadmap covers the analysis of key needs of the marketplace and customers, possible markets development within several scenarios, estimation of future demand for particular types of FCEVs and respective requirements including potential attitudes, measures and activities and argumentation lines of stakeholders. It will also require comprehensive analysis of technological innovation and product development based on identification of future dynamics. Thus, the FCEV roadmap allows considering both technological and market sides providing a combination of market pull and technology push approaches. The process will generate a roadmap demonstrating new products and technologies, which are important in achieving the set goals and a business map containing economic appraisal and comparison of alternative paths of future development. In addition, the roadmap should provide a detailed analysis of market pull, including the following:

- Areas of product's application determining the demand for technological solutions.
- Specificity of different segments of FCEV markets.
- Balance between technological facilities and consumers' needs.
- Economic estimation of technology trajectories.
- Analysis of stakeholders.
- Recommendations aimed at support of market-oriented technologies and products.

It will also pay special attention to description of technology push factors:

- Technologies that provide competitive advantages for FCEVs.
- Technological limitations.
- Priority technological tasks.
- Revealing of technological «forks».

The principal structure of the FCEV roadmap is presented on the Fig. 2:

The roadmap template includes four major layers:

1. Technologies. This layer contains the description of the prospective technologies within the identified time horizon. It provides a SWOT-analysis of these technologies that summarises benefits and limitations of each technology. It also provides a forecast of target properties required to satisfy market needs and a set of the main technological tasks necessary to be done to reach these features. Finally, it gives an opportunity to estimate prospects for each technology in terms of readiness for implementation and potential effect.
2. Products. This layer provides a brief description of prospective products in terms of readiness for commercialization and potential effects for researched area. It also estimates potential time of commercialization and the most prospective market niches for each product.
3. Markets. There will be elaborated scenarios of potential FCEV market development based on the eagle eye view approach. The roadmap will provide a brief description of main market's features and possible strategies for each scenario and

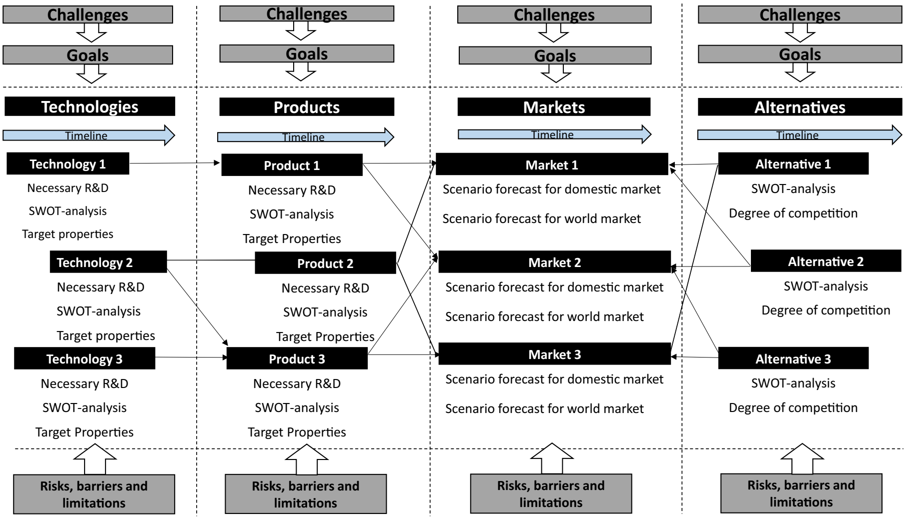

Fig. 2 Structure of roadmap

each market. Thus, all markets should be ranked from the most prospective down to the less ones.

4. Alternatives. The roadmap also reveals possible development of alternative products and solutions. It takes into account the dynamics of the main product properties, opportunities of export of these products and their cost.

For each layer, it is necessary to consider challenges and a set of relevant goals taking into account potential risks, the most significant particular challenges for FCEVs markets, to reveal obstacles that could hamper the FCEVs market development, and assess key risks and threats.

The complete roadmap illustrates the links between the key technologies for FCEVs, the consumer properties of existing and advanced FCEVs, the most promising products and their respective market shares, volumes and growth rates. It highlights the structure of potential demand for innovative products and outlines their most prospective markets. The roadmap also provides an assessment of technical capabilities required for manufacturing of products with the most preferable consumer properties, which would allow generating the significant competitive advantages for the FCEVs.

Being of practical value, the FCEV roadmap demonstrates optional paths of building added value chain “technologies–products–markets”. Such paths/trajectories are aimed at detailed description of possible strategies of commercialization on particular markets—what kinds of FCEVs should be produced; what level of their consumer properties will allow them to compete against other similar (conventional and new) goods at different time periods; what kind of new technologies should be introduced to obtain the required product properties.

The FCEV roadmap reveals alternative ways to achieve the market goals and to choose efficient allocation of resources. The roadmap takes into account manufacturing and market developments, prospects of technologies, products and services contributing to the design of complex innovation value chains ranging from technology to market entrance of FCEVs and allows building strategies for linking FCEVs development with other related industries (suppliers and consumers of related products/technologies). It integrates the expert community views on innovative development ways in FCEV and related areas, provide a set of well-grounded trajectories of innovation development and indicated principal “bifurcations” as points of the key decisions to be made. The roadmap should be regularly updated to enhance its practical value for decision making.

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