TOP–NEST

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Value chain analysis of hydrogen in Finland

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Introduction

This work is mostly based on the recent hydrogen road map for Finland [1]. Information of this report is reviewed and analysed with the focus on path dependence [2].

In general, it should be noticed that the change of the paradigm is mostly driven by major global stakeholders in EU, Korea, Japan, and major automotive original equipment manufacturers (OEM).

Therefore, when discussing the possibilities for new path creation in Nordic countries (including Finland) it must be done by closely monitoring the development of global hydrogen and fuel cell technology.

The case study of Finland is focused on issues, which would create possibilities to initiate new technologies in certain niches taking into account the specific situation in Finland.

The case here is the role of industry by-product hydrogen in path creation of hydrogen infrastructure for Finland.

Finland has peculiar characteristics compared to many other countries, when discussing the build-up of hydrogen infrastructure.

There is an EU directive in preparation, which would oblige member counties to build sufficient amount of refuelling and charging stations. In October 2013 there were no information available if there will be requirement for hydrogen refuelling stations (HRS) for Finland and how many stations should be build. Preliminary, a distance limit of 300 km between HRS has been mentioned in Article 5 Hydrogen supply for transport in A proposal for a Directive on the deployment of alternative fuels infrastructure (COM(2013) 18)1.

In Finland there are very significant amount (17 000 t/year) of by-product hydrogen produced in chlor-alkal industry [3]. A major part of this could be used for vehicles, when fuel cell vehicles are commercialised. The production of by-product hydrogen is also relatively distributed, but located mostly in southern Finland with highest population density.

The use of inexpensive by-product hydrogen in the first phase of hydrogen infrastructure build-up would also favour relatively centralised hydrogen production in the latter phase, as delivery infrastructure would be built around the by-product hydrogen. With other words, inexpensive by-product hydrogen may have a central role in path creation for hydrogen infrastructure in Finland.

Another important industrial factor in Finland is availability of biomass and high level technological knowledge in biomass and solid waste gasification.

The Finnish company Metso has delivered the world's largest biomass gasification plant to Vaskiluoto in Vaasa [4]. In addition Metso has delivered the first power plant using first solid recovered fuel (SRF) gasification [5].

Gasification of biomass is a step in liquid biofuel production (biomass to liquids, BTL). On the other hand, hydrogen can be produced from biomass by gasification and this has been a topic of intensive research in many countries, including USA [6].

[1] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2013:0018:FIN:EN:PDF

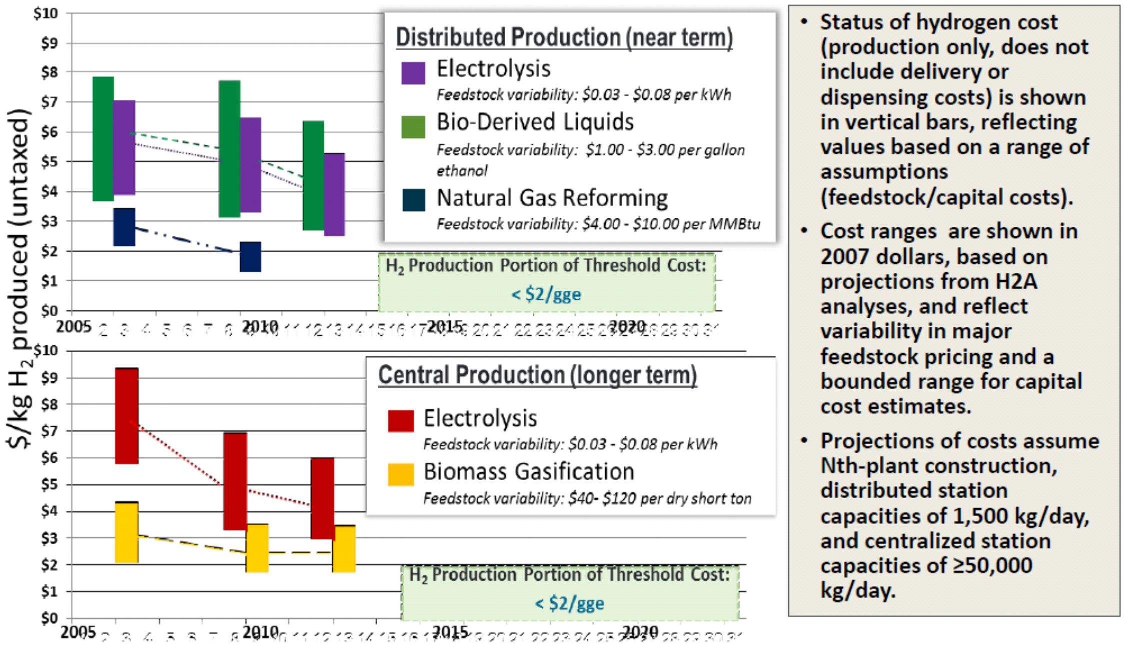

Figure 1. Economics of hydrogen production via gasification, from [6].

The energy efficiency of hydrogen production by gasification of biomass is significantly higher compared to production of other fuels [7]. This will favour hydrogen as soon as sufficient demand is available.

As the gasification and gas purification processes are common for both BTL and hydrogen production, there is possibility for win-win situation, instead of detrimental competition. As discussed later, hydrogen production by gasification of biomass/waste is not a short term option, as it must be done in large scale and final purification step may need to be done by liquefying. However, production of hydrogen production by gasification of biomass/waste would favour the general path of centralised hydrogen production and road delivery in Finland.

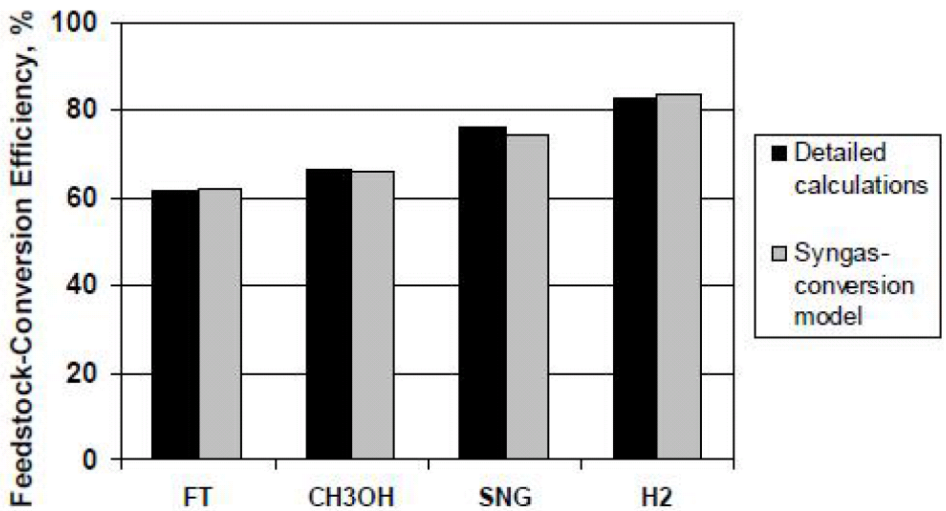

Figure 2. Efficiency for biofuel production [1, 7]. (FT=Fischer Tropsch diesel, CH3OH = methanol, SNG = synthetic natural gas, H2 = hydrogen)

1. Value chain characteristics

1.1. Main activities/segments of the value chain

1.1.1. Production of hydrogen

Concerning the production of hydrogen, the special feature of Finland is by-product hydrogen from chlor-alkal industry.

The use of industry by-product hydrogen would create an opportunity to replace significant amount of fossil (imported) fuels in first applications. As the value of by-product hydrogen for different use now is only 0-1 €/kg (0-30 €/MWh), a large part of this hydrogen could be economically used for vehicles, where the value is 5-10 €/kg (delivered). Since this hydrogen would replace expensive imported fossil fuel, the benefits for Finnish economy are clear and measurable.

The key issue for all forms of centralised hydrogen production is cost and efficiency of delivery and distribution. This is studied in DOE projects [8, 9]. It seems that reasonable distance for compressed gas delivery can in future be up to 300 km, see Chapter 1.1.5.

The production is located in few places (map, figure 3), which are outside of main consumption centres. However, these sites are not very far for considering road delivery, if the cost-efficiency of road delivery can be improved.

Another key issue here is the cost for upgrading hydrogen to the quality ISO 14687-2:2012, which is required for automotive applications (*ISO 14687-2:2012, Hydrogen fuel — Product specification — Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles*).

Another major production location in Finland is the oil refinery in Porvoo (50 km from Helsinki), where hydrogen is produced in large scale (108 000 t/year) using natural gas and steam methane reforming (SMR). The only supply for the natural gas in Finland is import from Russia. However, a number of LNG terminals is in preparation and investment subsidy for LNG terminals will be available[2]. This could, in turn, further accelerate the use of NG as a source of hydrogen for road transport before sustainable sources of hydrogen become cost efficient.

For this refinery based hydrogen the production cost is 1.5 €/kg, in NG cost is 30 €/MWh. The cost of this hydrogen is mostly dependent on NG price and therefore does not provide advantage to Finland compared to other countries.

However, if NG price remains low, also the use of this hydrogen would provide significant economic benefits to Finland, as it replaces even more expensive fossil fuels [1, pages 64-65]. Porvoo refinery is also located less than 50 km from Helsinki area, which is the largest consumption centre for transportation fuels.

Neste Oil has another refinery in Naantali. The usability of hydrogen from that oil refinery will depend on the investments either on NG grid in Finland or LNG terminals in Naantali, as inexpensive NG would be required for hydrogen production.

[2] http://www.tem.fi/energia/tiedotteet_energia?89519_m=112049, http://www.tem.fi/sv/energi/meddelanden_energi?89520_m=112057

The drawback of using NG would be the carbon dioxide (CO_2) emissions. While some reduction in CO_2 emissions can be achieved using hydrogen from NG, this hydrogen source should be seen as bridging technology towards CO_2-free hydrogen. Carbon capture and storage (CCS) may reduce the emission level of central hydrogen production from NG by SMR.

In general, there are and will be number of hydrogen centralised production units in southern Finland, not far from the main consumption centres.

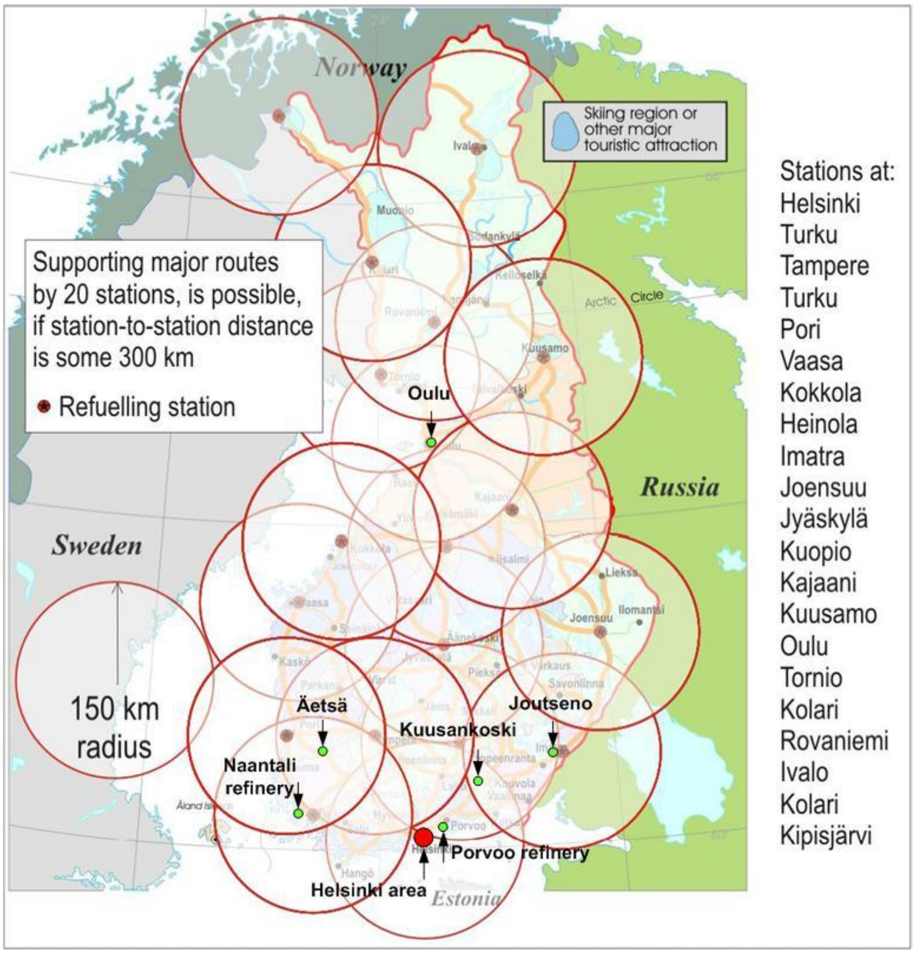

Figure 3. A lay-out for hydrogen stations in Finland with the main hydrogen by-product locations (from [1], with additions).

As discussed in the introduction, in Finland there is high level of knowledge and industrial activity for the gasification of biomass and waste.

This is important, as it provides the way to use parallel existing infrastructure and technology, which are also developed for the production of liquid biofuels.

Large scale gasification plants should not be located too far from raw material sources due to logistic costs.

A major issue for hydrogen produced via gasification is the purification and quality assurance cost for this hydrogen, as there are very many potential impurity components. Increase of impurity levels in standard ISO 14687-2:2012 and development of more cost efficient quality assurance method would significantly increase possibilities for hydrogen from gasification.

The increase of impurity levels in standard ISO 14687-2:2012 is not possible, before more information is gained on the contamination processes of automotive PEMFC systems. Developments of materials (catalyst, membrane) may improve PEMFC technology so that higher impurity levels are possible in the future.

A number of companies are producing hydrogen in Finland, see Table 1 [3]. Hydrogen production in Neste Oil Naantali refinery (about 10 kt/year, 300 000 m^3/day) is not included in this table. Otherwise, there have not been major changes for the information in this table.

Table 1. Hydrogen production sites in Finland [3]. (CS: Chlorine sodium hydroxide electrolysis, S: Sodium chlorate, SMR: Steam Methane Reformer, SR: Steam Reformer WE: Water Electrolysis)

Region (= NUTS level 3)	Plant site	Owner	Capacity [10^3 m^3/day]	Process / source	Current Use / Remarks	Availability
Itä-Uusimaa	Porvoo	Fortum Oil and Gas Oy	3300	SMR	Refinery	Captive
Varsinais-Suomi	Raisio	Linde	17			Merchant
Kymenlaakso	Voikoski	Oy Woikoski AB		WE	from hydropower	Merchant
Kymenlaakso	Voikkaa	Oy Finnish Peroxides			H_2O_2 production	Captive
Etelä-Karjala	Joutseno	Kemira Oy	55	CS		By-Product
Etelä-Karjala	Joutseno	Finnish Chemicals Oy	115	S		By-Product
Etelä-Karjala	Joutseno	Finnish Chemicals Oy	63	CS	hydrochloric acid	By-Product
Satakunta	Harjavalta	OMG Harjavalta Nickel Oy	60	SR Naphta	Metals	Captive
Satakunta	Aetsa	Finnish Chemicals Oy	240	S		By-Product
Lappi	Oulu	Kemira Chemicals Oy			H_2O_2 production	Captive
Lappi	Oulu	Eka Chemicals	30	CS	Hydrochloric acid and fuel	By-Product
Lappi	Oulu	Eka Chemicals	90	S	Hydrochloric acid and fuel	By-Product
Uusimaa	Espoo	Oy Woikoski AB				Merchant
Uusimaa	Helsinki	Linde	12			Merchant
Itä-Uusimaa	Porvoo	Borealis Polymers Oy	161	Ethylene		By-Product

As shown in the table, most of the hydrogen is produced for industrial use (captive). In addition, some of the by-product hydrogen has high value use close to production site. A smaller amount of hydrogen is produced for merchant purposes. However, a very large amount (>10 000 t/year) by-product hydrogen has no high value use or no use at all.

The key issue here is the value of sold hydrogen for the producer of by-product hydrogen. When hydrogen is replacing peat or wood chips in heat and power production, it has a value of 15-30 €/MWh, meaning about 0.5-1€/kg. Hydrogen sold to a customer in HRS will have a tenfold price (exc. taxes) compared to its current use 5-10 €/kg.

The cost of purification, quality assurance, delivery and pressurising are determining the final value of industrial by-product hydrogen. In case of chlor-alkal by-product hydrogen it could be estimated that there are relatively inexpensive ways to upgrade hydrogen quality to the level of standard ISO 14687-2:2012 and the cost for the quality assurance could also be kept minimum. When hydrogen is produced from NG these cost are higher, but reasonable if production scale is large enough, which is the case in centralised production.

However, it should be noted that all these cost items (added value) take place in Finland. Therefore, the benefits for the national economy will be high even if relatively expensive domestic hydrogen is replacing imported fossil fuels.

Currently, it is difficult to estimate, which share of the hydrogen could be used for road transport purposes. If hydrogen is used for chemical production, it is not available. If it is used for heat and power production, it could be partially or completely replaced by other fuels.

In addition to these points, there are several future opportunities for by-product hydrogen. For example, if Kemira Chemicals would change raw material for their Formic acid and hydrogen peroxide production from heavy fuel oil to LNG, this would mean additional 4000 tons of hydrogen available for vehicle use in Oulu. Neste Oil has planned expansion of Naantali refinery capacity, which would mean 5-8 times larger hydrogen production capacity.

1.1.2. Production of fuel cells for transportation means

In Finland there is currently no production of fuel cells for transportation means. There is knowledge at VTT for producing PEFC systems and operating systems with low quality hydrogen [10, 11, 12], but this knowledge has so far not been commercialised.

The production of hydrogen fuel cell systems for transportation means is strongly dependent on production scale [13]. In addition, the development of technology is extremely IPR intensive. Therefore, it is expected that there is very little room for independent fuel cell system producers for automotive use. It can be expected that automotive fuel cell system manufacturing is done by automotive companies, possibly even several companies together. This excludes the possibility for independent actors.

The major factor driving the value chain for fuel cell stack to the direction of hierarchy is the complexity of fuel cell systems. Namely, the system design and operation is dependent on the properties ann performance of membrane electrode assembly (MEA) including gas diffusion layer (GDL). A change of this key component has unpredictable consequences in stack and system behaviour requiring, in the worst case, redesign of system design. This means that when FCEV are mass produced, automotive OEM would be completely dependent on component suppliers, as change of component would mean redesign of the PEFC system with costs of (tens) of millions €.

This means that the current value chain for PEFC stacks may change dramatically. It is possible that all major automotive OEM will have their own MEA and GDL manufacturing lines in the future. This means that one or more current MEA manufacturers may leave the business (or sell membrane, instead of MEA), as they see no major customers for MEA in automotive OEM in the future.

This development may seriously hinder the PEFC commercialisation, as high quality MEAs are key component for both independent stack and system manufacturers and for automotive OEM, who still not have their own MEA supply chain.

Alternative value chain development is in the direction of captive governance. In this type of structure both independent stack/system manufacturers and automotive OEMs are dependent on MEA manufacturers. However, only automotive OEMs have financial power to establish own MEA manufacturing lines, if needed.

The opportunities are in clever application of fuel cell products and component/material manufacture for the stack and systems.

1.1.3. Production of equipment for storage and transport of hydrogen

The Finnish steel industry (Ruukki group) already supplies the raw materials for the manufacturing of the hydrogen pressure vessels and pipes in Europe [1]. In future, hydrogen pressure vessels and pipe systems or parts of them could also be manufactured in Finland.

The Finnish company Woikoski is developing refuelling station [1]. Woikoski's refuelling station concept is a mobile unit with own innovative technology.

1.1.4. Integration with other energy production technologies

There has been some discussion about hydrogen production for the grid support in road map report [1]. However, in the near and medium term the needs for grid support using electrolysis of fuel cells are not so large in Finland, as the amount of intermittent (solar, wind) renewable electricity production also in the future will be small compared to other countries (Germany, Denmark, Ireland). There also is a strong transmission grid within Finland and strong transmission capacity to neighbouring countries, which enable the export of renewable electricity in times of high production.

The exemption for this may be island of Ahvenanmaa with excellent wind resource and limited transmission capacity to mainland of Finland and Sweden.

A larger opportunity to integrate hydrogen production with other energy production technologies may exist in combination of hydrogen production via gasification of biomass and waste with heat and power production.

1.1.5. Distribution of hydrogen for transportation means and related infrastructure

As discussed in 1.1.3 and in ref [1] Woikoski is developing own mobile hydrogen refuelling stations.

It has been discussed in the road map report [1], that the use of mobile hydrogen refuelling station is beneficial in many ways. In the beginning of the deployment mobile hydrogen refuelling stations can serve a small number of vehicles in the first points of locations. In the later phase, these mobile stations can be replaced by larger stationary stations. In this scenario the mobile hydrogen refuelling stations are then moved to new locations.

What is not discussed is the scale of economics in hydrogen delivery, which is a topic of intensive study [8,9]. In order to understand the cost of delivery a large number of parameters must be analysed.

The economics of road transport can be expected to improve significantly, as the delivered hydrogen in each truck can be increased [14].

Figure 4. New type of hydrogen delivery truck [14].

In the earlier study from 2007, the cost of delivery for gaseous hydrogen would be excessive, if transport distance is increased [15]. In this study, the net delivery of 244 kg per truck was assumed. The results of the 2013 DOE study on Hexagon indicate that even up to 1350 kg per truck could be transported [14]. The difference of factor of 5.5 improves delivery of trucked hydrogen significantly.

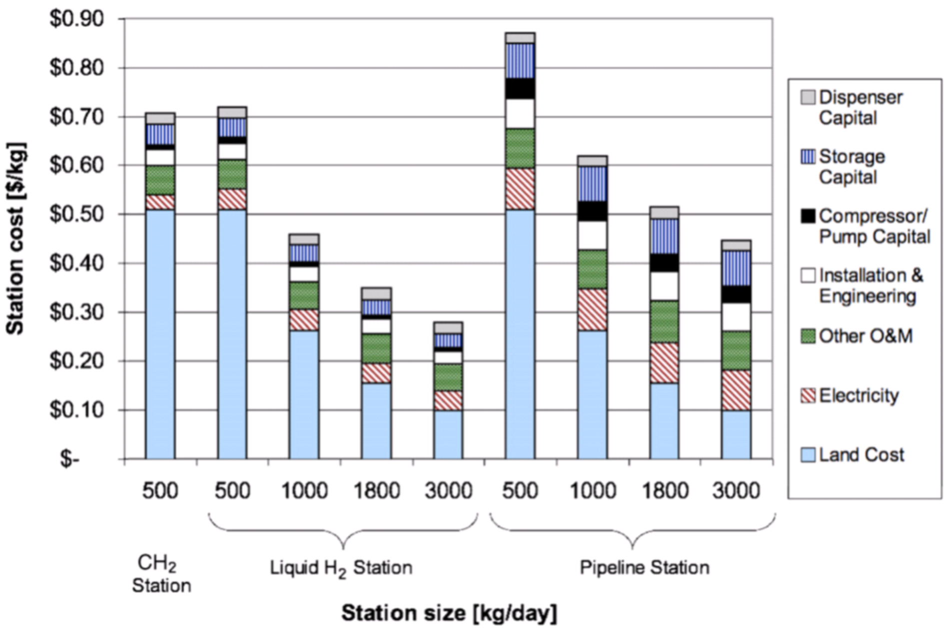

Figure 5. Transmission costs breakdown ($/kg) for hydrogen as a function of flow and distance for the three different transport modes considered in [15] (CH_2: Compressed hydrogen).

However, the effect of better delivery efficiency was already considered in [15] "*The largest impact on the delivery cost occurs when switching to higher-pressure tube trailers (i.e. double capacity at the same cost) because it reduces the number of truck trips, thereby lowering capital costs and reducing* *the amount of fuel required. These trucks are being developed and certified for H2 delivery in the US and throughout the world."*

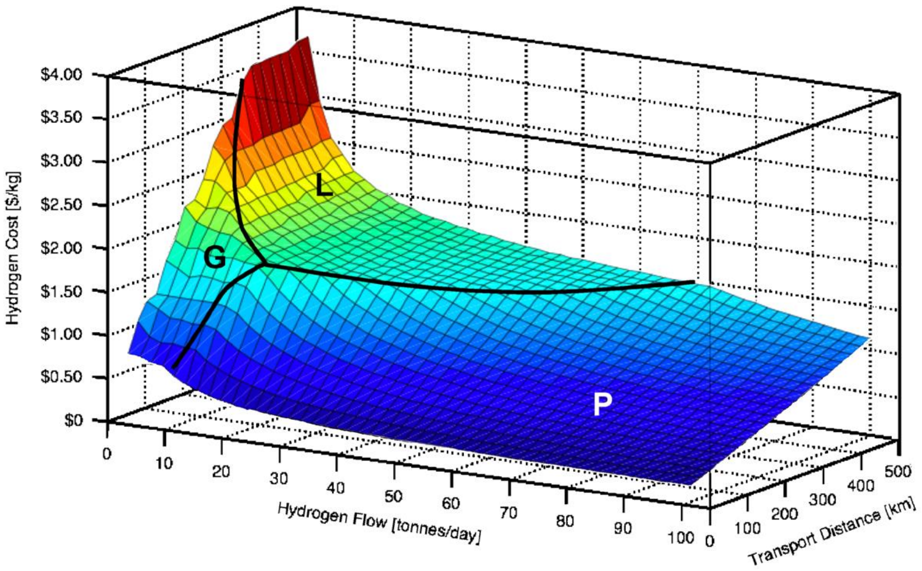

Figure 6. Minimum hydrogen transmission costs as a function of hydrogen flow and transport distance [15].

Currently, Woikoski is delivering gaseous hydrogen in 200 bar bottles with 247 kg H_2 per truck [1]. Woikoski plans to increase the pressure level to 300 bar, which would improve the economics of the delivery. When considering the upper weight limit for road transport, the chosen solution is about 100 composite bottles with about 400 kg total payload capacity. Woikoski will take 6 such transport units in operation in 2013. As the maximum weight for vehicles in in Finland will be increased from 60 to 76 tons in the near future, this may further improve the payload up to 550 kg delivery.

However, this is still far from the 540 bar and 1350 kg delivered by Hexagon [14]. If later on legal issues allow the use of large composite cylinders on European roads, the economics of road delivery are further improved. As the transport cost is common for all forms of centralised production (also NG-SMR with CCS), there will be intensive research efforts to improve economics of delivery both as compressed gas and in liquid form [9].

When comparing possible future road transport of compressed hydrogen and in liquid hydrogen, there is large number of both economic and technical issues to be considered.

Liquefying hydrogen and transporting it as liquid is not an energy efficient way to distribute hydrogen. On the other hand, if waste is used for the gasification, then raw material cost is very low, as well as CO_2 emissions.

In the EU-project HyWays, finalised in 2008, there has been discussion about local hydrogen production [16] with focus on year 2050.

Taking into account the improved economics of hydrogen delivery, the cost-economical production methods for the hydrogen are more determined by total cost of hydrogen as delivery cost is decreased. Therefore, the figure 6 from HyWays project is not too relevant for the near term, when market introduction of hydrogen and FCEV is considered updating.

The combination of hydrogen production by gasification and liquefying hydrogen would improve purity of hydrogen. This would remove one of the major barriers, which is purification and quality assurance of hydrogen, when it is produced from complex hydrocarbons, especially from waste.

In addition to cost and energy efficiency, reliability of components (especially compressors in hydrogen refuelling stations) shall be considered as well as purification and quality assurance of hydrogen.

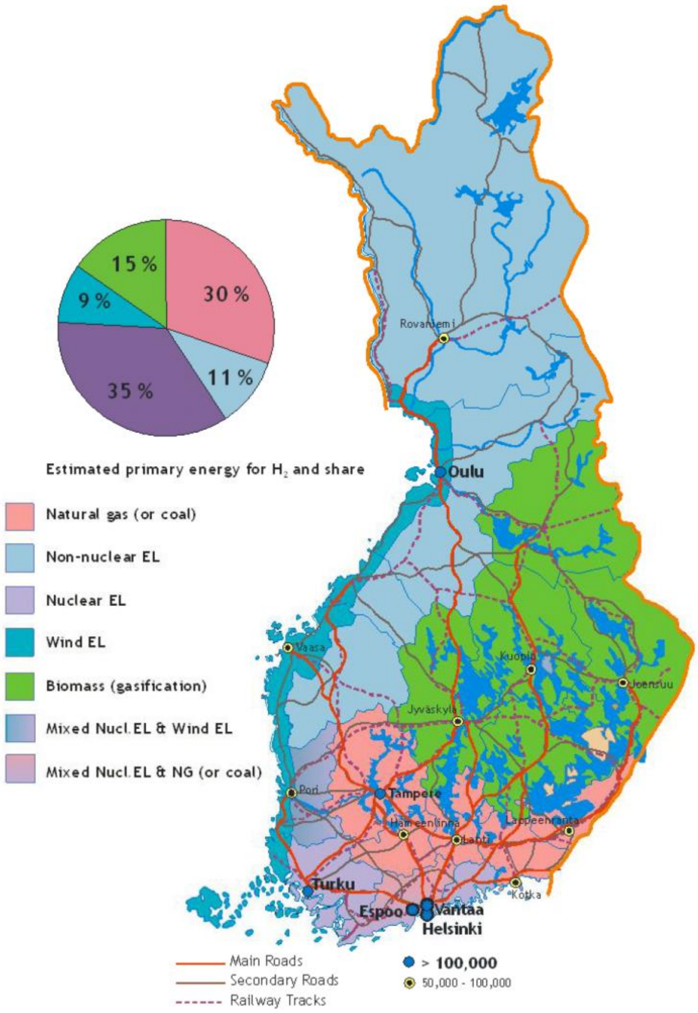

Figure 7. Hydrogen production feedstock divided by primary energy and regions [16, p. 38].

Woikoski sees the use of by-product hydrogen and road transport as highly attractive option for the first phase of hydrogen infrastructure as by-product hydrogen is inexpensive and purification and quality assurance (for ISO 14687-2:2012) are relatively straight forward. When economical transport distance is exceeded, hydrogen can be produced locally, with truck delivery as back-up option. This is especially important in the market introduction phase, as the station may be the only one in that region. The reliability of single HRS must be very high.

In conclusion, there is an urgent need of evaluating the options of centralised and distributed hydrogen production in Finland.

1.1.6. Marketing and sales of hydrogen and fuel cell cars

There are no marketing or sales of fuel cell cars in Finland and no sales of hydrogen for automotive fuel. However, due to a possible EU directive [17] there can be a need to build a network of hydrogen refuelling stations in Finland. This could trigger also marketing or sales of fuel cell cars in Finland.

Currently, there are no incentives for purchasing or leasing fuel cell vehicles in Finland. However, vehicle purchase tax is based mostly on CO_2 emission. Therefore, hydrogen fuel cell vehicles can potentially have significantly lower vehicle purchase tax than other cars. This would be true especially for vehicles, which have large weight and powerful engines.

1.2. Main supporting activities

1.2.1. RD&D undertaken in companies

There has been and is still a clear interest in working machine industry (Konecranes, Cargotec) for hydrogen fuel cells. However, the companies do not see demonstrations possible without clear interest from their customers [18,]. In general, the working machine industry is following the needs of their customers. I any customer is willing to pay extra price for a new solution, this can be done. However, the companies are not developing products without orders from their customers [18]. Therefore, creating marked on this segment requires regulations or subsidies that would attract customers of these companies.

The working machine industry is, however, developing and commercialising series diesel hybrid vehicles [19]. The use of fuel cells in these vehicle platforms is relatively straight forward in case the cost and availability issues for FC systems and hydrogen can be solved.

The Fuel Cell Finland Industry Group (FCF) operates in parallel to Tekes Fuel Cell programme 2007-2013. In August 2011, a joint demonstration project was launched, called Demo2013, which is working towards a major fuel cell demonstration in the Port of Helsinki, Vuosaari Harbour. Increased public acceptance is a key aim, as is awareness of the viability of the technology among policy makers. During the second half of 2013 there will be an info-centre in Gatehouse building sharing information about fuel cells, their applications and hydrogen safety. Several round tours for public, professionals, decision-makers and students and schools will be arranged.

The demonstration will encompass a fuel cell car (Hyundai) and associated hydrogen refuelling station from Woikoski Oy. A fuel cell back-up power system by Finnish Company T Control, based on a Dantherm system, will also be tested on Telia Sonera's base station. The long term test started already on 5th September, 2012. A smaller PEMFC backup power system based on methanol will be presented by company Fitelnet. There will a remote monitoring of a 50 kW PEMFC stationary power unit DuraDemo operated by VTT and located in a chemical factory in Äetsä, 300 km away. The project partners would like to test materials handling vehicles from various suppliers in the heavy-duty environment of the harbour, as they see considerable potential for fuel cell powered cargo-handling. However, the first versions will be electric hybrid systems and available later in 2015. Also a 50 kW SOFC stationary power unit using natural gas and bio gas is postponed and will be demonstrated later in 2015-2016 by company Convion Oy. Cargotec was planning to participate in the demonstration project in the Port of Helsinki. In the beginning of 2013 there was a change in the R&D policy. Cargotec is currently following the technology with no public plans for demonstration projects.

Currently, Woikoski is the only company actively doing large scale RD&D work in the field of automotive fuel cell and hydrogen delivery.

1.2.2. RD&D undertaken by public research organisations

RD&D in Finland has been concentrated at VTT Technical Research Centre of Finland. The general description of VTT fuel cell activities can be found in recent report [20].

VTT is dominating research and hydrogen and fuel cells in Finland. However, hydrogen and fuel cells seems not to be in the focus of the new strategy of VTT. Instead the focus seems to be in gasification of biomass and liquid biofuels (BTL).

However, hydrogen production and gas purification is a common topic and creates possibilities for synergy for both BTL and automotive grade hydrogen production.

When considering R&D activities on vehicle applications, VTT has demonstrated the hybrid fuel cell forklift [10]. In the last years, the focus of RD&D at VTT has been the development of simulation tools for optimising fuel cell systems and how to use industrial quality hydrogen in PEFC systems.

Arctic power, a unit of Rovaniemi University of Applied Sciences has been active in developing electric snow mobile [20, 21]. A part of that project has been demonstration of hydrogen fuel cell as range extender for electric snow mobile.

1.2.3. RD&D funding support by public agencies

The domestic RD&D funding has been stable during the Tekes Fuel Cell programme period (2007-2013) in the range of 5-10 M€/year. However, after this programme the domestic RD&D funding is expected to decrease significantly. This will be, however, compensated partially by EU funding (FCH JU), as Finnish stakeholders have been very successful in FCH JU calls. Tekes Fuel Cell programme has created a solid knowledge base in Finland leading to success, when competing EU funding.

1.3. Companies/actors involved in each segment of the value chain

The value chain analysis will focus on hydrogen fuel production and distribution.

The value chain for hydrogen production and distribution is shown in Figure 8 (courtesy: Spinverse Oy).

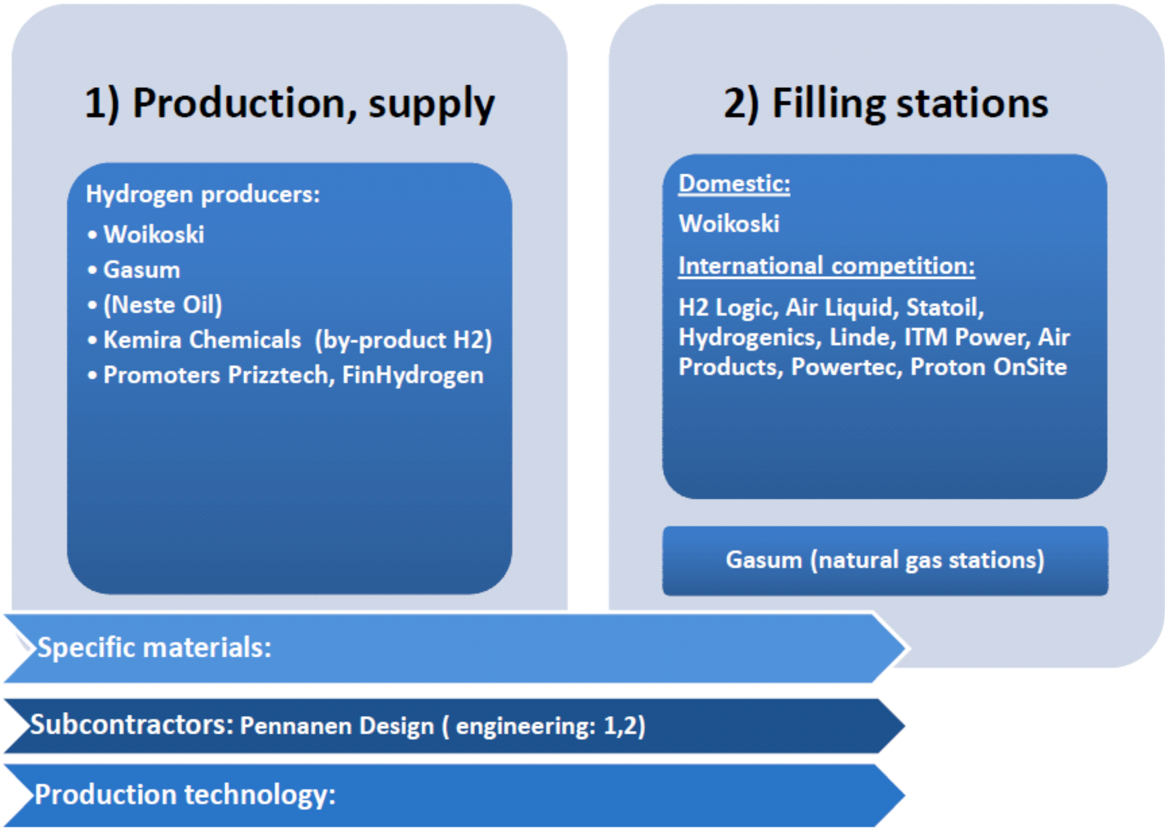

Figure 8. Value chain for hydrogen production and distribution in Finland.

The fuel supply part of the value chain can have a large domestic share. Hydrogen is a local fuel and should be produced in Finland.

There are number of alternatives for hydrogen production and delivery. As discussed in other parts of this work, by-product hydrogen and road delivery is the most probably early market option.

For the development of the HRS infrastructure, the coming *Directive on the deployment of alternative fuels infrastructure* will have high importance. If only number of stations and distance between them are criteria, container based small capacity (50-100 kg/day) stations have clear advantage.

In the long term future, biomass based hydrogen, electrolytic hydrogen and natural gas based hydrogen are competing with each other. There might not be a clear winner and the forms of production may also complete each other, occupying different parts of Finland and different station sizes.

Value chain for FC hybrid vehicles using hydrogen is shown in Figure 9 (courtesy: Spinverse Oy). This vale chain has been developed to understand how FCEV development will affect the value chain of possible FC hybrid vehicles manufactured in Finland. Most of these FC hybrid vehicles would not be for road transport.

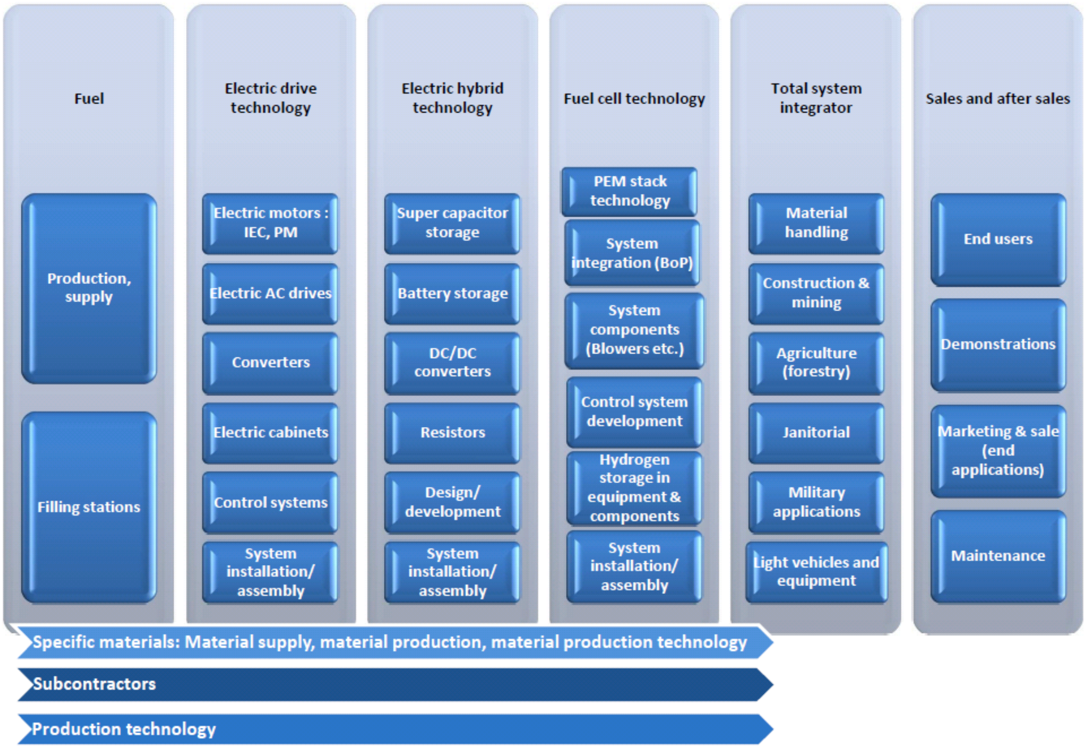

Figure 9. Value chain for FC hybrid vehicles using hydrogen.

Since the FCEV manufacturing is most probably not taking place in Finland, the parts of the FCEV value chain are not too much dependent on the domestic decisions. However, as many of the components are also the same as in FC hybrid vehicles, the working machines the global development will have impact on Finnish industry, the part “total system integrator” in FC hybrid vehicle value chain.

The build-up of the HRS infrastructure may have significant impact on the FC hybrid vehicle development in Finland. If HRS for road transport would be available for non-road vehicles this would enable more efficient demonstrations as HRS cost is always an issue, especially if FC hybrid vehicle fleets are not large.

1.4. Value chain governance structure

When discussing value chain for hydrogen infrastructure, there are two main cost items: hydrogen production and transport as well as hydrogen refuelling stations (HRS).

The formation of value chains for both HRS and hydrogen production will be depending on the governmental subsidies. Therefore, there are no real market conditions in the beginning. The operation of the HRS will not be profitable in the beginning and must be subsides, too.

Due to subsidies, the formation of the value chain is dependent on the subsidies. Some forms of production and distribution may be preferred, which have significant impact for the profitability of the production and distribution of hydrogen.

In addition, the location of the first hydrogen stations may be politically decided. The location of the first hydrogen stations will effect on the choice of hydrogen.

Some stakeholders may be active in both HRS manufacturing and hydrogen supply (Woikoski). Some, possibly majority of the companies may also be both hydrogen producer and HRS owner and operator. This would be the situation in the beginning, when number of hydrogen suppliers and HRS operators is very limited. In this case, the form of governance is hierarchal.

HRS owner and operator need to purchase HRS either as components of as a complete station. Especially in the beginning HRS will have small capacity (50-100 kg/day) and are often based on the containers. In this case, HRS supplier is a turn-key supplier for the lead firm. Therefore, the form of governance is modular.

In general, the regulation will be high in the build-up phase of the hydrogen infrastructure. As the operation of the HRS must be subsidised there can be requirements for the cost of hydrogen as well as availability of the HRS.

2. Key technologies and assessment of their technological development stage (dominant design, disruptive or incremental)

2.1. Technologies for hydrogen production, distribution and storage

Woikoski has developed mobile hydrogen refuelling station (HRS) for international market. The designed mobile HRS has daily capacity of 50 kg (10-15 fillings) and is therefore suitable for the early introduction of fuel cell vehicles in new markets and areas. As discussed above, this mobile type of station is especially well suited for the market introduction phase of hydrogen vehicles.

Woikoski is also expanding hydrogen production capacity in Finland and has already invested in new hydrogen road transport vehicles. Currently, Woikoski is transporting 500 ton of hydrogen annually.

Currently, there are no commercial activities for hydrogen production from biomass. However, VTT has the required knowledge for gasification of biomass and production of ultrapure hydrogen.

VTT has long experience on material research, in which hydrogen issues must be taken into account.

2.2. Technologies for fuel cells

VTT is mostly participating in public private funded fuel cell projects in the field of PEMFC for transportations. In addition, VTT has done contract research on stack development.

VTT has activities in battery research and hybrid systems. As all PEMFC systems for automotive applications are going to be hybrid system, batteries are key technology for achieving cost optimised fuel cell hybrid systems.

3. Market characteristics

Finland is currently clearly behind other Nordic countries, when it comes to commercialisation of fuel cell and hydrogen technology for automotive applications.

Currently, only Woikoski is having major R&D effort on commercialisation of the technology in Finland. However, also for Woikoski Finland is not considered as the main market.

The good economics of centralised hydrogen production would favour large vehicle fleets (hundreds of buses and thousands of cars) in. In practice, this is achievable only if a large amount of fuel cell vehicles are introduced in small time or in single step. This would require either new regulation or additional subsidies or both.

4. Geographical scope

In Finland the population is concentrated in the southern Finland, see Figure 10. In the northern Finland the main population centre is in Oulu region.

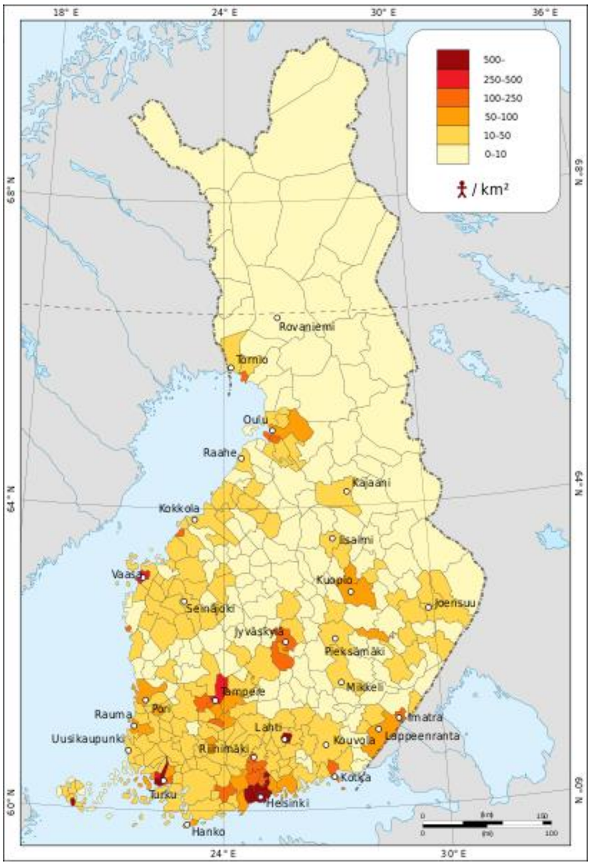

Figure 10. Some more detailed (and official) map of population density[3].

When comparing this Figure with the location of industrial by-product hydrogen sources in Figure 3, it is clearly seen that by-product hydrogen can be economically transported to the majority of HRS

[3] http://en.wikipedia.org/wiki/Demographics_of_Finland

with larger capacity. Only eastern Finland as well as northern Finland would need other source of hydrogen in the market introduction phase.

5. Institutional context

In Finland there is no specific governmental subsidy available to hydrogen or fuel cells. However, all new energy technologies may receive investment subsidies (Act on Discretionary Government Transfers 688/2001), which are decided case by case. Fuels cells as new technology may receive investment subsidy up to 40%.

In Finland there has been a large fuel cell R&D programme for fuel cells in 2007-2013[4] funded by Tekes, as discussed in Chapter 1.2.1. With a help of that programme fuel cell technology has been developed in Finland. Tekes' fuel cell programme has also helped Finnish stakeholders in international networking, which is a necessity in fuel cell technology development. One example of success of this programme is success of Finnish companies and research institutes in FCH JU funding calls.

6. Path dependencies

As has been discussed above, the situation in Finland is peculiar. Here are some key issues summarised.

- Finland has a large amount of by-product hydrogen and the sites are geographically well distributed.
  - This hydrogen has currently a low value (0-1 €/kg) in most cases
  - Centralised production favours road transport
- In Finland there is currently low interest for hydrogen fuel cell vehicles (cars, buses) and no market at all. In near term, no change for this can be expected.
- In Finland there is a long tradition of R&D for liquid biofuels from gasification of waste and biomass. This creates opportunity, but can also be a threat, if synergies are not understood and there is unhealthy competition for R&D money.

These are also important part in the path creation process, see Table 2. Based on these initial conditions, following path could be created. However, when discussing path creation is should be emphasised that the most important for the path creation is legislation (regulation) and subsidies. These will define playfield for entrepreneurs and inventors. This is a pure political decision.

Market for the first few thousands of vehicles is created using almost only by-product hydrogen from most cost-efficient locations. The first market expansion (tens of thousands of vehicles) is then achieved using centralised hydrogen production from refineries.

Further expansion (market penetration > 10%) is then achieved using hydrogen from centralised production using domestic technology (biomass, waste) as well as hydrogen produced by electrolysis.

[4] http://www.tekes.fi/en/programmes-and-services/tekes-edistaa-yhteistyota-ohjelmien-avulla/fuel-cell/

In Finland, the on-site production using electrolysis would be in near- and mid-term limited to small hydrogen refuelling stations in remote locations. When costs of electrolysis and renewable electricity decrease, electrolysis could also take over the position as dominating production method in Finland.

Important issue would be increased use of by-product hydrogen for other high value non-automotive use. This would enable gradual build-up of hydrogen road delivery infrastructure.

Non-governmental organisations (NGOs) may or may not support the build-up of hydrogen infrastructure. They may have importance, when, hydrogen infrastructure is expanded. However, the initial phase is dictated by political decisions due to need of significant subsidies.

Availability of inexpensive electricity and natural gas would accelerate the development of hydrogen infrastructure. Therefore, the development of LNG infrastructure as well as additional nuclear energy would not possess a barrier.

One important issue is the level of knowledge among different stakeholders. Lack of information may hinder the possible changes in the regulation, which could be needed.

Also, H_2 from industry cannot be done in small scale (investments in purification, quality assurance, transport, stations), but requires large initial fleets.

The competition between hydrogen could be a barrier. However, as many of the same technologies (biomass gasification, gas cleaning, gas purity control) are required in both biomass based hydrogen and biofuel production, there is also a strong synergy.

Table 2. Path dependencies and path creation processes for H2/FC in Finland (adapting Simmie, [2])

Initial conditions	**Path creation process**	**New path establishment processes**	**Barriers to new path creation**	**Landscape change outcome**
Large amount of by-product hydrogen Company (Woikoski) interested in creating H2 infrastructure Technology advantage in gasification of waste and biomass, but also creating lock-in Limited amount of stakeholders and funding institutes.	Legislation or subsidies for FC busses Increased use of by-product hydrogen for other purposes encouraged Commercialisation of domestic hydrogen refuelling station Tax exemption for fuel cell cars (5 years) Well planned fulfilment of EU directive for alternative fuels	Tax exemption (next 10 years) for hydrogen Conversion of all major city bus fleets Production of low cost H2 from waste and biomass by gasification Establishment of cost optimised H2 infrastructure	No consensus of single large location of FC vehicle fleet leading to locations, which are not optimal for Finland Delivery cost of H2 to consumers remains high Non-optimised locating of first hydrogen stations leads to poor utilisation, poor economics, poor PR Cost of quality assurance (QA) remains high No success in low-cost H2 production from biomass/waste Unhealthy competition between hydrogen and biofuels	2050 nationwide H2 infrastructure with 50-100 stations 30% of vehicles FCEV and > 50% of km done by FCEV Almost all buses use hydrogen. Domestic renewable fuels (H2, BTL fuels, electricity) cover all transportation fuel needs

An important issue is to estimate how much extra car drivers are willing to drive for filling less expensive hydrogen. Traditionally, Finnish drivers are willing to drive surprisingly long distances for finding less expensive gasoline. If a similar behaviour could be expected for hydrogen filling, then large hydrogen filling stations should be placed within reasonable pipeline distance (10-30 km) from locations of inexpensive by-product hydrogen.

Since the delivery of hydrogen may be 1 or even 2 €/kg-H_2 cheaper next to the production point, this may attract large amount of drivers. Important issue here is the risk of getting stranded, if there is not enough hydrogen in the tank for reaching the refuelling station with cheap hydrogen. If FCEV are more plug-in type hybrids [20], this risk is almost eliminated, as FCEV can reach the station using electricity only.

All locations, where by-product hydrogen is produced, (Äetsä, Joutseno, Kuusankoski and Oulu) would be excellent, as they are close to main traffic routes. Also Neste Oil refinery in Porvoo would have a beneficial location enabling pipeline distribution to Helsinki area.

As shown in the paper of Yang and Ogden [15], pipeline distribution favours high amounts of hydrogen. It is also relatively economical in short and medium distances (25-200 km), when high amounts of hydrogen are distributed. For smaller amounts the road delivery is preferred [15].

7. Conclusions

In Finland the current infrastructure and initial condition for path creation seems to favour centralized hydrogen production with hydrogen road transport. There are many open issues, which affect the creation of the path.

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