SAFETY ASPECTS OF LAND-USE PLANNING SCENARIOS FOR A FUTURE INFRA STRUCTURE WITH HYDROGEN RE-FUELLING STATIONS

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ABSTRACT

Hydrogen is currently gaining much attention as a possible future substitute for oil in the transport sector. Hydrogen is not a primary energy source but can be produced from other sources of energy. A future hydrogen economy will need the establishment of new infrastructures for producing, storing, distributing, dispensing and using hydrogen. Hydrogen can be produced in large-scale centralized facilities or in smaller-scale on-site systems. Large-scale production requires distribution in pipelines or trucks. A major challenge is to plan the new infrastructures to approach an even safer society regarding safe use of hydrogen. The paper will, on the basis of some scenarios for hydrogen deployment, highlight and evaluate safety aspects related to future hydrogen economy infrastructures.

1.0 INTRODUCTION

Alternatives to oil and internal combustion engines may be introduced in a larger scale in the next decades due to concerns about the transport sector's potential contribution to environmental problems and oil depletion. One promising road transport alternative is hydrogen fuel cell vehicles. This paper investigates the safety concerns that may be attributable to a road transport system using hydrogen in comparison to the current oil based system.

Most major car producers have designed various demonstration vehicles using hydrogen in internal combustion engines or fuel cells and several demonstration programmes have been set up featuring hydrogen refuelling stations, passenger cars and buses. Major hydrogen initiatives for R&D have been started up in United States, Japan and Europe featuring various ambitious goals. For example, in Japan a goal of introducing 5 million hydrogen vehicles by 2020 has been mentioned [1]. There are however still very large hurdles to be overcome before hydrogen fuelled cars may become competitive to current vehicle types. Major hurdles comprise development of inexpensive and durable fuel cells, improved technologies for storing hydrogen on-board vehicles and development of affordable ways of producing and distributing hydrogen [2].

Hydrogen is not a primary energy source but has to be produced from other sources of energy. Currently large-scale production of hydrogen is applied in fertilizer production using mainly natural gas steam reforming. There are various well-known ways of producing hydrogen either directly from coal, natural gas, oil or by using electricity for electrolysing water. The hydrogen can be produced on-site at the filling station or in larger production plants from where it will have to be distributed to the filling station in pipelines or by truck and the latter can carry hydrogen in either compressed or liquid form. In the transport sector hydrogen is only used in a relatively limited number of demonstration projects, in many of which hydrogen is produced via water electrolysis or small scale reformers on-site at hydrogen filling station demonstrations. If hydrogen is to be introduced as a major fuel in the transportation sector a system for producing and distributing hydrogen will be needed [2].

In this paper we identify and discuss safety aspects related to various potential future hydrogen infrastructures in a system perspective.

2.0 HYDROGEN SAFETY ISSUES

In general all activities belonging to the energy chain also have a safety implication, starting from the extraction of the primary energy source, through feedstock preparation, conversion to an energy carrier, conditioning, distribution and conversion to final service. The EIHP working group on safety concludes that overall hydrogen is no more hazardous, than conventional fuels. However, says this group, the many ways in which hydrogen differs from conventional fuels make it necessary to perform detailed risk assessment for every stage in the hydrogen supply chain [3].

In contrast to LPG and gasoline vapour, hydrogen is extremely light and rises rapidly in air. In the open this is generally an advantage, but it can be dangerous in buildings that are not designed for hydrogen. Many countries' building codes, for instance, require garages to have ventilation openings near the ground to remove gasoline vapour, but there is often no high-level ventilation. Hydrogen released in such a building collects at roof level, and a resulting explosion can be extremely destructive.

Hydrogen has been used widely for more than a hundred years in large-scale industrial applications. There have been incidents with hydrogen, as there have been with other materials including gasoline, LPG and natural gas. In general, though, experience shows that hydrogen can be handled safely in industrial applications as long as users stick to the appropriate standards, regulations and best practices.

Modern, established technologies within energy supply and transportation are at high safety standards. This ensures a secure, safe and user friendly supply of energy in stationary, transport and other system applications. It is the result of a long learning process within these technologies. Future infrastructure systems for Hydrogen applications, as new storage media and refuelling stations, need at least to have the same high safety standards as the established technologies.

The present main use of hydrogen is within the industrial production of ammonia and petroleum refining processes. Also here many years of experience make the large scale industrial applications very safe in general, but comparing with the application of natural gas the frequency of accidents is reported 5 to 20 times higher for Hydrogen [4]. The following accident causes have been identified:

- Mechanical failures of vessels, pipes, etc., often caused by Hydrogen embrittlement or freezing
- Reaction with pollutants (e.g. air)
- Too low purity of Hydrogen
- Accidents caused by smaller releases due to poor ventilation or flow back of air under ventilation
- Accidents during purging with in-active gases
- Non functioning of safety equipment
- Wrong operations (by staff)
- Failure in evaporating system (e.g. valve failure) or not intended ignition / fire / explosion

Zalosh [5] reported in 1978 that in 80 % of the Hydrogen accidents ignition occurred and hereof 65% caused an explosion. 40% of all the Hydrogen leakages were not detected and therefore it was considered to install appropriate detectors in Hydrogen systems.

There also exist long year’s experiences applying pipelines and underground storages. There are a number of Hydrogen pipelines of very different lengths and materials operated in different countries with the largest ones situated in Germany and France with 215 and 290 km, respectively. The German pipeline was established in 1938 and been operated since, while the French is operating since 1966.

The operating pressure in existing pipelines range from few MPa to more than 100 MPa [4, (page 6)]. There are no accident reports for these pipeline networks and the operators have positive experiences operating the pipelines. The same applies to the underground storage. There are substantial and positive experiences on handling Hydrogen safely within industries using approved routines by skilled workers.

3.0 TRANSPORT SYSTEM IN THE GREATER COPENHAGEN AREA

The region considered in this study is the Greater Copenhagen area populated by 1.8 million people. The region around the capital is the most densely populated part of Denmark featuring a well-planned road system in combination with efficient inter-city and regional train systems and urban S-train and metro systems. Passenger cars are used in more than half of the passenger trips contributing almost 80% of all the passenger transport (measured in kilometres travelled by passengers). Main part of the goods transport is shipped in trucks [6]. An estimated 900 filling stations serve around 760,000 passenger cars [7]. Each year passenger and goods road transport in the Greater Copenhagen area consumes an estimated 70PJ diesel and petrol fuel. Since 1980 road transport fuel consumption has grown by 50%, or 1.9% per year, due to growth in passenger and goods traffic. The number of kilometres driven by passenger cars almost doubled while kilometres driven in trucks grew by around 60% over the 22-year period [8].

Figure 1: Area of Greater Copenhagen of about 2900 km^2

3.1 Scenarios for hydrogen production, storage, distribution, retail and use in the Greater Copenhagen area road transport system by 2050

In this study we analyse and compare safety issues in three different scenarios for hydrogen use in passenger road transport in the Greater Copenhagen area. A rather long transition period may likely be needed before fuel cell vehicles can effectively substitute current internal combustion vehicles. In a business as usual scenario hydrogen is not envisaged to make any serious contribution in the next decades [9]. The time frame considered is therefore 2050. The purpose of this analysis is not to forecast what may likely happen but rather to describe safety aspects related to possible future hydrogen systems.

Figure 2 illustrates today’s road transport fuel system as well as three different future systems in which all passenger cars are using hydrogen.

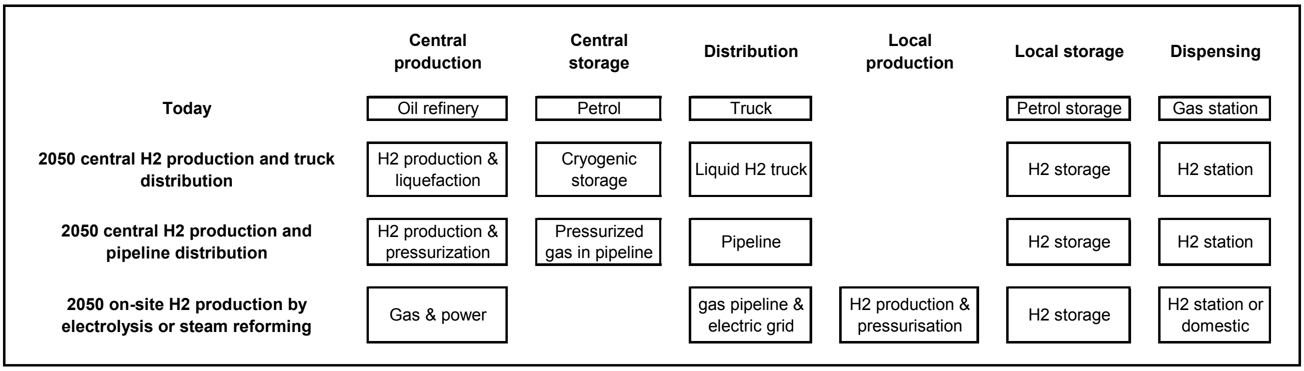

Figure 2: Comparison of today's petrochemical system to three hydrogen systems.

In the centralized production scenarios hydrogen is produced in large plants either using natural gas reforming, coal gasification or electrolysis and hydrogen is compressed and transported in pipelines or liquefied before storage in cryogenic tanks. Liquid hydrogen is distributed in trucks and pressurized hydrogen is distributed in pipelines.

In the decentralized scenario hydrogen is produced on-site at the filling stations or directly in domestic applications using natural gas steam reforming or electrolysis as well as pressurization and local storage.

Future road transport energy consumption depends upon developments in the number of vehicle kilometres driven as well as developments in vehicle energy efficiency. **Table 1** exemplifies how the Greater Copenhagen transportation system might develop if society chooses the hydrogen pathway.

Table 1. Main assumptions in H2 scenarios.

	Today	**2050 central truck**	**2050 central. pipeline**	**2050 decent.**	**Source/comment today**	**Source/comment 2050**
Passenger cars [million]	0.76	1	1	1	Based on average cars per person in Denmark (0.38)	Based on assumption of growth to 0.53 cars per person
Vehicle km (billion)	9.9	20	20	20	Based on average 15 km car driving per person in GC area	Based on assumed doubling
Fuel per vehicle km [petrol/hydrogen]	57.7 g	4.5 g	4.5 g	4.5 g	Based on an average fuel consumption of gasoline fuelled passenger cars of 13 km/l or 2.53 MJ/km	Based on and estimate by Weiss et. al. (2003) [10] for a highly optimised future hydrogen fuel cell car using about 0.54 MJ/km.
Yearly fuel consumption	594 mio. tonnes	90 thousand tonnes	90 thousand tonnes	90 thousand tonnes		
Fuelling stations	900	450	450	450	Oliebranchen in Denmark 2004, [7]	Based on assumed halving
Avr. distribution distance (km)	200 km	100 km	100 km	-	Current refinery situated approximately 100 km from centre of region	Based on siting closer to region than current situation
Avr. annual sales per fuelling	660 tonnes	200 tonnes	200 tonnes	200 tonnes		

	Today	2050 central truck	2050 central. pipeline	2050 decent.	Source/comment today	Source/comment 2050
station						
Sales per day per fuelling station on average/max [tonnes]	2/4	0.5/1	0.5/1	0.5/1		
Tanker truck capacity	19.5 tonnes	400 kg	-	-	Bossel et. al. (2003)[11] Capacity of 33 tonnes with hanger	Bossel et. Al. (2003) [11] Capacity of 500 kg, but not fully emptied
Tanker truck trips per year [thousands]	31	225	-	-		
Yearly tanker truck driving distance [mio km]	6	22	-	-		
Trucks per day per station	0.1	1.4	-	-		
On-site storage capacity refuelling station	>30 tonnes	>600 kg H2	<500 kg H2	>700 kg H2		assumed to be larger than one tanker truck capacity, while the storage can continuously be refilled using the pipeline

Hydrogen has a very low volumetric energy density and is therefore much more bulky than gasoline. Even though hydrogen fuel cells are more energy efficient than internal combustion engines much more tanker truck transports are needed in a hydrogen system than what is necessary in the current petroleum system unless the hydrogen is distributed in pipelines or produced on-site [11].

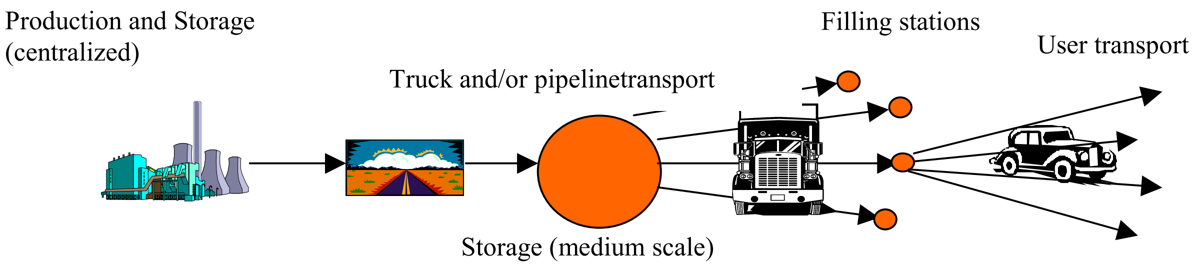

Figure 3. The picture [12] shows a schematic production distribution chain for centralized Hydrogen production and distribution. The transport to and from the medium scale storage can be by truck and/or pipelines. The on-site production will not need such a medium scale storage.

We just give a qualitative assessment of the risks, but consider in general transport of hydrogen in pipelines as the safer way compared to truck delivery. The general risks coming from the small on-site production facilities is assumed to be in between the pipeline and truck delivery, as on the one hand there is an additional reactor on-site, but on the other hand it is a fixed installation avoiding e.g. loading unloading procedures.

For the truck transport Brockhof [13] made an assessment for the Danish roads. The accident rates by Brockhof are based on a collection of Danish accident descriptions (based on police reports) and road characteristics from 1982-1986. Accident rates relate to accidents involving trucks (not defined in detail). There is no information about the severity of the accidents. The accident rates are transformed into regression formulae for different road types, and accounting for truck percentage and traffic intensity. The final accident rates are calculated using information about the total length of the road types in Denmark. An average accident rate for trucks on all roads of 39 pr. 100 million vehicle km is reported. For rural roads (80 km/h limit) the number of accidents is 30 and for urban roads (50 km/h limit) 420. For our scenario that gives for today 2.3 accidents pr. year, while hydrogen delivery by trucks may raise the yearly accident rate to 8.6 not considering any improvements.

But this is not the only problem connected to hydrogen systems. Advantages and disadvantages of each of the systems are summarized in **Table 2**.

Table 2. Advantages and disadvantages of various fuelling systems. For further discussion on the issue see [2, 10, 11, 14, 15].

	Today	**2050 centr. Truck**	**2050 centr. pipeline**	**2050 dec.**
Advantages	- No need for pipelines - Existing system for extracting, refining, distributing and dispensing gasoline and diesel - Internal combustion engines have been refined over decades and are cheap and reliable - Internal combustion drive systems can be further optimized and can be combined with electric engines in hybrid vehicles - Oil products currently cheaper than H2 - Oil can be produced from unconventional sources such as oil sands/shale, coal or gas-to-liquids	- No need for pipelines - Centr. H2 production cheaper than dec. - Can use CH4, coal or electricity for H2 prod. - Carbon dioxide releases from H2 production may potentially be stored in geological formations - Hydrogen fuel cell vehicles emit only water vapor	- No need for trucks - Existing CH4 pipelines may be used for H2 transmission - Centr. H2 production cheaper than dec. - Can use CH4, coal or electricity for H2 prod. - Carbon dioxide releases from H2 production may potentially be stored in geological formations - Hydrogen fuel cell vehicles emit only water vapor	- No need for pipelines/trucks - Can use CH4 or electricity for H2 prod. - Possible positive combination with electric grid/renewables - Hydrogen fuel cell vehicles emit only water vapor
Disadvantages	- Combustion of diesel and gasoline contributes to global warming and health problems - Oil is a limited energy resource	- New dispensing system needed - Breakthrough automotive H2 technologies needed (on-board storage and fuel cell cost, durability and efficiency) - Expensive H2 production - Expensive H2 liquefaction - Expensive LH2 distribution - Large number of trucks - If using CH4 or coal additional transmission and	- New dispensing system needed - Breakthrough automotive H2 technologies needed (on-board storage and fuel cell cost, durability and efficiency) - Expensive H2 production - Expensive pipelines needed - If using CH4 or coal additional transmission and distribution capacity is needed increasing	- New dispensing system needed - Breakthrough automotive H2 technologies needed (on-board storage and fuel cell cost, durability and efficiency) - Dec. H2 production even more expensive than centralized production - H2 production based on fossil fuels releases carbon dioxide - If using CH4

		distribution capacity is needed increasing international trade with these products - H2 production based on fossil fuels releases carbon dioxide - CH4 and coal are limited resources - Hydrogen energy chain can be energy intensive	international trade with these products - H2 production based on fossil fuels releases carbon dioxide - CH4 and coal are limited resources - Hydrogen energy chain can be energy intensive	additional transmission capacity is needed increasing international trade - Hydrogen energy chain can be energy intensive

These reveal some of the major opportunities and problems relating to future hydrogen systems. Main drivers for hydrogen systems are the need to reduce oil consumption and for reducing emissions from road transport. Main obstacles are that technical breakthroughs are needed in on-board hydrogen storage and fuel cell durability and efficiency and that major reductions in cost of fuel cells and hydrogen production are needed to make hydrogen competitive to oil. Furthermore, building up a system for producing and distributing hydrogen will be an expensive task [2].

It is not yet certain whether one of the three hydrogen scenarios described here will stand out as a preferable option. Each scenario has some advantages and disadvantages over the others. Centralized production of hydrogen is cheaper than decentralized on-site production but costs related to distribution, either in trucks transporting liquid hydrogen or in pipelines transporting compressed hydrogen gas, will be quite expensive. Centralized production, based on natural gas steam reforming or coal gasification, is currently the cheapest option while electrolysis remains a costly option. On the short term coal and natural gas may therefore be used as so-called bridging technologies on the path to longer-term decentralized systems in which so-called plug-in "vehicle-to-grid" fuel cell cars may be integrated in the electric production system using electricity for charging batteries at "low-peak" hours and selling electricity back to the grid at "peak-load". Thus, initially hydrogen systems may probably be based on centralized hydrogen production and truck distribution. Next step may be pipeline distribution and ultimately decentralized hydrogen production based on renewable electricity may be introduced [2]. As discussed in the next section each system involves different safety aspects.

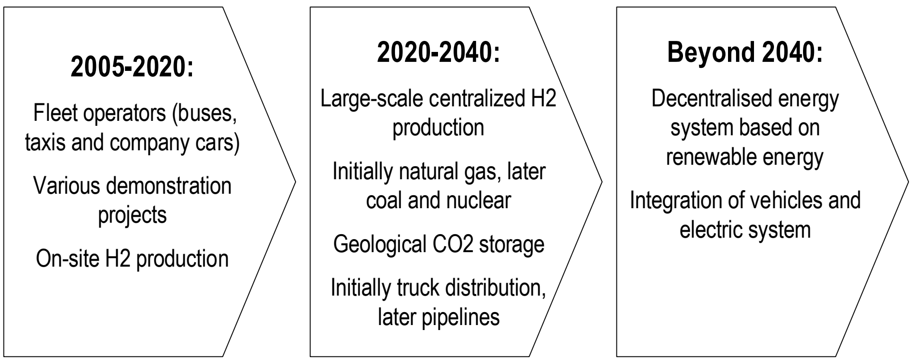

Figure 4: Possible development of hydrogen system

It should be noted though that alternative pathways to the hydrogen route exist, including hybrid vehicles, battery electrical vehicles, bio-fuels, etc. [14, 16, 17, 18].

3.2 Safety aspects related to scenarios

Below, in **Table 3**, a possible centralized supply scenario is qualitatively compared with an on-site local one. The assessment is not considered complete, also as the scenarios are not yet defined in great details. The purpose is to give some first indications on possible safety issues to be discussed further during the development and test of the specific applications.

NASA is recommending to design and to use an inherently safer systems approach [19]. The scenarios that have been drawn up here are still in the very early stages, which therefore also provide many good and cost effective possibilities for the application of the inherently safer design approach as e.g. described by Trevor Kletz [20]. One principal of this approach is to simplify systems (”W*hat you do not have can't leak*”). Other general measures are to minimize e.g. to store as little hydrogen as possible and any other measure that is likely to reduce the overall risk and hence give better and safer systems.

Thus for the future hydrogen re-fuelling system a measure to increase safety could be by reducing the amount stored on the dispensing site, which could be done by pipeline systems and /or smaller on-site production systems for Hydrogen. In case of the truck delivery that is most likely to be the case at least in the beginning it may be considered to avoid the unloading of the tankers into a buffer storage by just leaving the trailer at the refuelling station. As it is now the tank procedure takes about 10 to 15 min. A time reduction here will not only give a better service, but may also reduce the risk for the drivers and passengers due to shorter stays at the refuelling station assuming that a safe “rapid refuelling system” can be provided (high pressures needed) or to have over night refuelling systems at low pressure for the decentralised scenario.

Nevertheless, this is reproducing more or less the well-known systems for gasoline and LPG re-fuelling stations. It could be that a fuel cartridge system (e.g. the fuel in a box concept from Shell [9]) provides a much better solution. It could be easier and quicker to re-fuel changing whole car tanks using an appropriate technical support system, the cartridges can easily be maintained frequently while they are recharged at remote sites. These examples shows, even though they may seem unrealistic to achieve for different reasons, that it will be worthwhile to thoroughly discuss different safety scenarios at the very early stages of a new hydrogen economy to find safe solutions for the future systems before too many applications will have penetrated the market.

Table 3. Safety aspects related to centralized versus on-site production of Hydrogen

Application	**Environment Centralised scenario**	**Environment : local scenario**
H2 production site	Potential placement in remote area, closed industrial site, industrial safety rules fully applied, access only for skilled workers	Placed at refuelling station also in urban areas, closed industrial site with fully applied safety rules, small production quantities compared to centralized facility
Main and regional storage	Placement in less populated areas possible, closed industrial site, industrial safety rules fully applied, access for skilled workers	Not necessary
Transport by pipelines	Industrial application , placed between e.g. production and main/regional storages	On site
Transport by trucks, rail, ship	Necessary, route planning necessary, potential risks very much dependent on the region (topology, meteorology, population density, etc.)	Not necessary
Transport by power grid	N.a.	Production by electrolysers
Refuelling site storage	Buffer storages evt. compared with compressors if lower pressure storage is used	Ditto
Refuelling the vehicles	Unskilled drivers may spent 10 to 15 min on-site, industrial safety standards (e.g. with regard to ignition sources) will not be fully applicable, a number of passengers will be in the vehicles (cars) and special safety precautions for them have to be taken. The same for tourist	Ditto

	long distance busses that need to refuel under a longer trip.	

4.0 CONCLUSIONS

The paper describes two main scenarios for a hydrogen production and distribution system in the Greater Copenhagen area. A centralised system's hazards are compared qualitatively to on-site systems. To reach public acceptance for the future hydrogen economy it is important to ensure a low frequency of accidents. Hydrogen has been proven to be safe in industrial applications, but a new aspect is the unskilled persons that will have to handle the hydrogen e.g. while refuelling cars. Therefore, it is essential to provide very safe as well as simple and easy-to-use equipment. Other questions that need to be solved are concerning the comfort the new technology will bring. It is often said that e.g. the radius for a car should be about 500 km pr. filling precisely as it is now. Other aspects here need to be addressed as well, e.g. will in the future scenario the drivers and passengers be allowed to be near or in the vehicle while refuelling (cars and tourist busses) or will they have to keep a certain safety distance? Or do we need to go back to the old refuelling service provided by the owner of the stations?

Concepts for the inherently safer design and appropriate safety systems including detection will be a good start to cope with Hydrogen safety aspects. For the introduction of the hydrogen economy it is important to gain fast experiences on the safety performance of the different applications. A general public safety monitoring programme for all the test facilities and early application could be very useful. The knowledge will help to develop excellent standards, well designed applications and good and operational procedures for installation and maintenance.

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