HyWays

Assessment of the Regional Hydrogen Demand and Infrastructure Build-up for 10 European Countries

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ABSTRACT

The infrastructure analysis in the *HyWays* project comprises an integral regional and supra-regional assessment of the hydrogen demand and supply development over time. An iterative process is pursued including intense stakeholder discussions within all the participating countries (Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Poland, Spain and the UK) and the regional modelling of supply and demand. High initial investments in infrastructure can be mitigated by a gradual local build-up. Once a significant demand exists, hydrogen costs at the pump range between 11 and 16 €-ct/kWh (1.1 - 1.6 €/l Diesel equivalent). Hydrogen use will take off mainly in densely populated centres and, during the transition phase, gradually expand towards locations difficult to supply. Hydrogen supply infrastructure build-up depends strongly on regional particularities such as the available feedstock, population density and geographic factors. Each delivery option is beneficial under certain conditions, with a trend towards centralized production for areas with higher population density in later phases.

INTRODUCTION

The implementation of advanced, highly innovative technologies such as hydrogen applications is not only a matter of achieving the right payback time. A transition towards a sustainable energy system involves changes at various levels of economy and society. Therefore, many industrial countries and regions are currently working on hydrogen roadmaps. The *HyWays* project is a comparatively large multiregional roadmapping activity in Europe (1).

Besides modelling of energy chains and the energy system, socio-economic modelling and stakeholder discussions, infrastructure analysis is one of the crucial tasks in this project. The essence of the infrastructure analysis task in *HyWays* is to create scenarios for the build-up of regional hydrogen demand and supply over time which take into account the available resources as well as national policies and stakeholder interests. The purpose is to evaluate different infrastructure build-up options in economic terms and to derive recommendations for the introduction of hydrogen as a transportation fuel in the next decades. This paper first describes the methodology used for infrastructure analysis in *HyWays* and then the key results and conclusions derived from this activity.

INFRASTRUCTURE ANALYSIS METHODOLOGY

The economics and technical aspects of developing hydrogen infrastructure have been studied by several groups for Europe (2, 3) and on an individual country level (4). The methodology of the *HyWays* infrastructure analysis goes beyond these by studying the 10 countries participating in *HyWays* (Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Poland, Spain, and the UK) one by one based on country-specific inputs agreed by a wide group of stakeholders. In this way, it will be possible to gain insights into the situation of each specific country as well as, when aggregated, into a large part of Europe.

Snapshot	**T1**	**T2**	**T3**	**T4**
Hydrogen vehicles EU25-wide	10,000	500,000	4 million	16 million
Calendar year (moderate penetration)	2014	2017	2021	2027
Share of population with local hydrogen access	~20%	~25%	~50%	~85%

Table 1: Time snapshots for base case with moderate market penetration of hydrogen vehicles

The infrastructure analysis task can basically be divided into the demand and the supply side, where the hydrogen supply of each area is required to be in line with the corresponding demand, but does not impose any feedback to the demand. Four snapshots T1-T4 are used as discrete time nodes. These phases are defined by the number of hydrogen cars which will be on European roads at each time. A connection to the calendar years can be established through hydrogen vehicle market penetration curves elaborated by the *HyWays* consortium (see Table 1). The infrastructure analysis focuses on the early phase of hydrogen deployment with a relatively low penetration of hydrogen vehicles (up to approx. 8%) because regional aspects are crucial in this phase. The spatial resolution for the analyses is based on the NUTS3 classification (5), resulting in approx. 1000 areas in the 10 *HyWays* countries involved.

In the transportation fuel sector a distinction is made between fuel/fuelling stations (FS) for local traffic and for long-distance traffic. This is mainly because the latter implies a continuous FS network along main roads (also in areas where there is no local use), while the former will only be situated in the areas where hydrogen users reside. The regional allocation of both FS types is treated separately. Hydrogen for stationary applications is also considered, but will be disregarded here.

In the first snapshot (T1), FS for local traffic hydrogen are only located in "early user centres". In each country, 4-6 areas or agglomerations are selected based on the qualitative evaluation of a list of regional indicators, namely local pollution, cars per household, size of cars, stationary use possibility, availability of experts, existing demo-projects, favourable hydrogen production portfolio (renewable energy sources, by-product hydrogen), customer base, political commitment and stakeholder consensus. For long-distance traffic in T1, a few "early corridors" are defined which mainly serve to connect the early user centres and to permit daily commuting in their vicinity.

The further regional rollout of hydrogen FS for local traffic in later time snapshots (T2-T4) is determined by a ranking of the areas based on weighted socio-economic indicators (catchment area population, purchasing power, cars per person). This is performed separately within each country and considers the assumed share of population to be supplied (see Table 1) and regional differences in the progress of market penetration. For the supply of long-distance traffic, all long-distance roads (motorways or E-roads, depending on the country) are equipped with hydrogen fuelling stations from T2; assuming by simplification that the same amount of hydrogen will be used for each km of road.

Three different fuelling station capacities (small, medium, and large, with 1, 4, and 10 dispensers, respectively) are considered. The number and size share of the FS required in each area is determined according to the calculated local traffic hydrogen demand, but on top of this, accessibility to the users must be achieved by a certain minimum number of FS within one area and with a certain overcapacity in order to compensate for fluctuations in FS usage. A common assumption is that 10-30% of all conventional FS must dispense an alternative fuel to achieve broad user acceptance (6). The long-distance traffic FS are calculated accordingly, assuming 80 km between two FS in T2 and T3 on average, and 60 km in T4 (multi-lane roads have one FS on each side).

The production and supply infrastructure to serve the hydrogen demand is mainly analysed using the *MOREHyS* model (Model of Regional Hydrogen Supply), which specialises in infrastructure build up analysis (7). *MOREHyS* is a technology-based (bottom-up), mixed-integer, myopic linear optimisation model. The objective function used for the optimisation, which is carried out sequentially, is annual cost minimisation for the whole country and the complete supply chain (production to dispensing) in each snapshot.

MOREHyS is applied separately for each country. A country is divided into areas, and all capacities and demand are described at this level. Hydrogen demand areas were defined on the basis of NUTS areas. Due to computing limitations, areas with similar indicators were combined. Every country consisted of 20 – 26 regions for the analyses. A distinction was made between urban and rural regions. Both types play an important role in the build up of hydrogen infrastructure.

A large amount of input data, assumptions and projections were employed for the described analysis. To achieve coherence within the project, assumptions from within *HyWays* were used whenever possible, and also some results from other models (e. g. the projected hydrogen demand from the energy market model *Markal*). The forecasts of fossil energy costs were taken from the *WETO*-H_2 study (8). Technology costs and performance data were mainly based on the *EUCAR-CONCAWE-JRC* study (9), along with reviews and updates by the project partners. Country-specific data such as anticipated feedstocks for hydrogen production were taken from discussions with the national stakeholders and literature research. For the full set of assumptions and input data used, reference is made to the *HyWays* web site(1), where detailed reports will be publicly available after completion of the project (midyear 2007).

In the base case scenario, the shares of hydrogen production feedstocks were set according to stakeholder perceptions. Furthermore, it was assumed that at any time 20% of the hydrogen is dispensed in liquid form (LH_2) in all countries except Norway (based upon consensus among MS project partners and national stakeholders). Other scenarios assumed greater shares of the population supplied, later supply of the long-distance road network, higher or lower market penetration rates over time, free (unbound) choice of feedstock shares, higher shares of renewables, and no dispensing of LH_2.

RESULTS OF INFRASTRUCTURE ANALYSIS

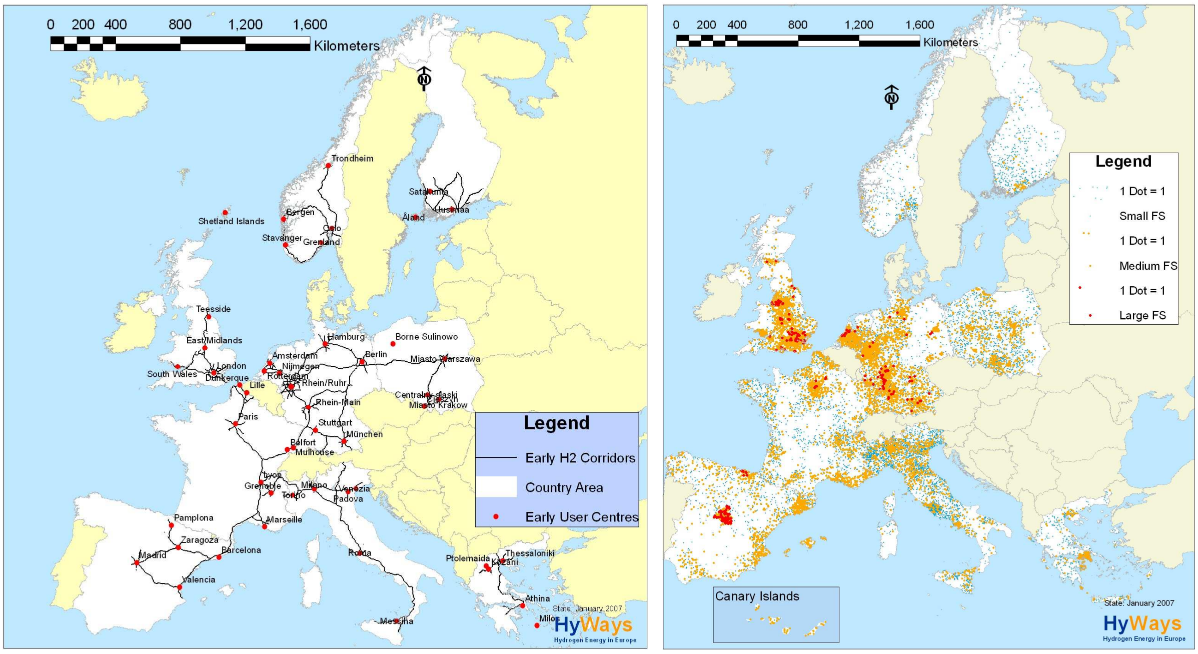


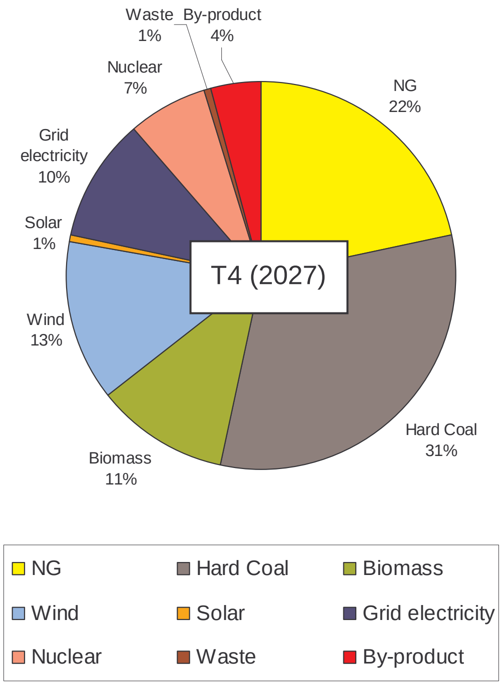
Figure 1: Early user centres and corridors for hydrogen in the 10 HyWays countries in T1 (left) and allocation of small, medium-size and large fuelling stations in T4 (right).

Figure 1 (left) shows the early user centres of all HyWays countries elaborated by the stakeholders, and the early hydrogen corridors. Note that the size of a user centre does not necessarily relate to its quantitative hydrogen demand. Most countries focus on densely populated areas for the early adoption of hydrogen due to the shorter distribution distances. Indicators like the availability of hydrogen experts, political commitment, existing demo projects and, to some extent, the availability of resources played a major role for the manual selection. Some countries include remote areas in the early user centre portfolio, namely Navarra (ES), Kyklades (GR), Koszalinski (PL), the Shetland Islands (UK), and the Åland archipelago (FI). There, stranded renewable energy resources can be tapped, and the requirement of a transit road network is lower due to the remoteness of these areas. In later phases, the existing local user centres will be extended and simultaneously new user centres will develop until almost the entire area of the countries is covered in the last snapshot.

Figure 1 (right) illustrates the approximate spread of small, medium-sized and large fuelling stations in T4. To supply the early user centres locally during T1, approx. 400 FS are sufficient for the 10 countries. The number of installed local FS rises with the increase in demand and the regional expansion of hydrogen supply and reaches approx. 17,000 in T4 (85% of population supplied; for comparison: 25,000 rather small FS are required if 100% of the population are to be supplied in T4). For long-distance traffic, approx. 500 FS are required to supply the early transit road network in the 10 countries. For the supply of all dedicated transit roads, between 1500 and 2000 FS are required.

The estimated rollout of hydrogen use and the regionally quantified hydrogen demand development were used to calculate the economically optimised production and supply infrastructure in the 10 HyWays countries, respecting the bounds for feedstock shares and technologies set by the stakeholders. Figure 2 shows the shares of feedstocks used for hydrogen production in the 10 countries in T4 respecting the country-specific bounds on the left, and the average specific hydrogen supply costs, along with the cumulated investment in hydrogen infrastructure aggregated for all countries on the right. It can be seen that, according to the perceptions of the stakeholders, more than

50% of hydrogen production in the later phase will be covered by coal and natural gas (mostly with carbon capture and storage). Renewables contribute approx. 25%, mainly wind and biomass, plus some renewables via the grid electricity pathway. While in the early phases, refuelling dominates infrastructure investments, this is dwarfed by production in the later phases. The total investment of the 10 countries until T4 (i.e. to reach a hydrogen vehicle penetration rate of about 8 %) is approx. 60 billion €. However, also conventional fuels required large investment: e.g. the IEA has recently estimated that a global investment of as much as 4,300 billion US-$ will be required in the oil sector until 2030 in order to maintain current production levels (10).



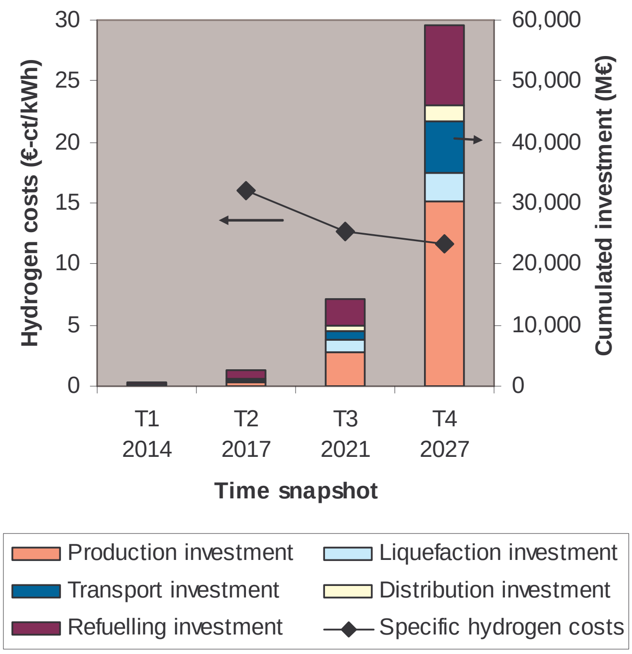


Figure 2: Feedstocks used for hydrogen production in T4 in the base case scenario (left) and aggregated investment and specific hydrogen costs in all snapshots (right).

The early phase (i.e. approx. 10,000 hydrogen vehicles EU-wide) is characterised by high specific hydrogen supply costs. The main reason is an underutilisation of the production and supply infrastructure due to technology-related capacity thresholds and the refuelling infrastructure's overcapacity required for user convenience. The overall hydrogen costs are very sensitive to the number of fuelling stations built; the establishment of an early long-distance road network therefore leads to a drastic cost increase in the initial phase.

Nevertheless, the total investment for the early infrastructure is limited to 30 - 120 M€ per country. Assuming approx. 1000 vehicles per country, this represents a high specific infrastructure investment per vehicle, mainly because the fuelling station utilisation is assumed to be very low. However, this is thought to be essential for the initialisation of hydrogen deployment and must be overcome by adequate policy measures. Substantially higher vehicle penetration rates will level out the costs to values between 11 and 16 ct/kWh hydrogen (1.1 - 1.6 €/l Diesel equivalent) in the medium term.

The rollout strategy for hydrogen in the snapshots T2-T4 is a further cost factor: In a transition scenario where a higher population share is supplied with hydrogen (i.e. 75% in T2, 100% in T3), a greater number of smaller fuelling stations are required. This leads to 10-20% higher specific hydrogen supply costs in the early phases (T2), which level off to 5-10% later (T4).

Figure 3 shows the shares of transport and distribution options over time for the base case (left) and two alternative scenarios (middle: 0% LH_2 demand, right: 0% LH2 demand and slower fuelling station build-up with higher utilisation). Centrally produced hydrogen that is transported to the target region via pipeline can be distributed from the pipeline terminal via distribution pipeline or CGH_2 truck. It must be pointed out that Figure 3 shows the model results of scenarios which are exposed to many sensitive factors (e.g. transport distances, fuelling station turnover/cars served, demand for LH_2, energy prices, density of fuelling stations in a region) and none of the scenarios should therefore be regarded as the "ultimate strategy".

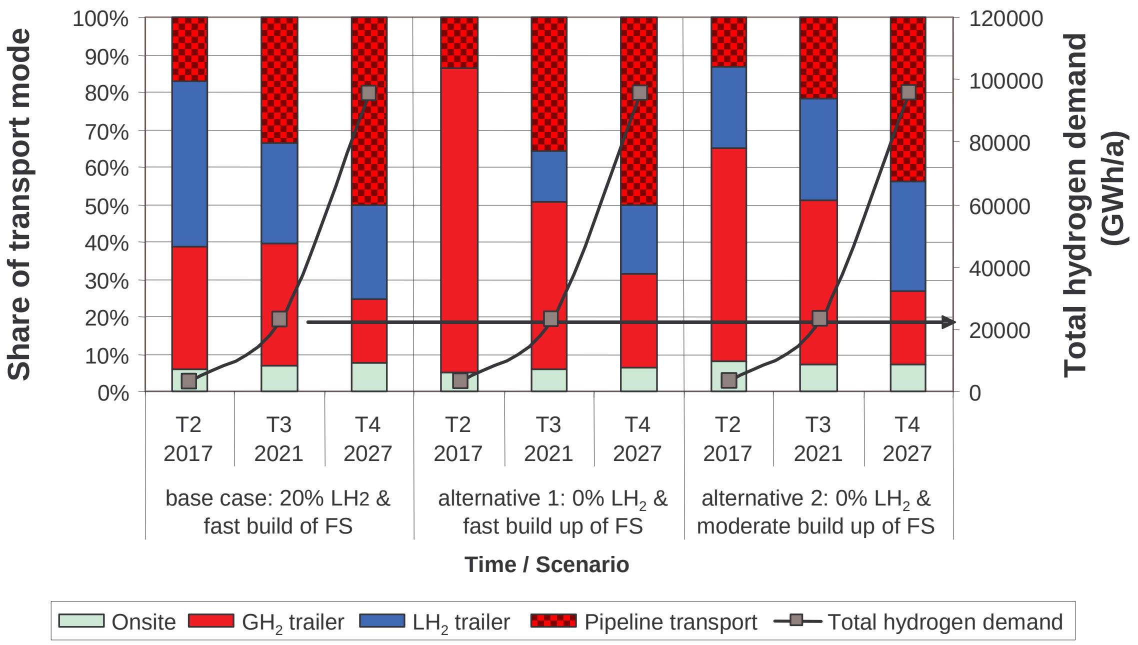


Figure 3: Share of hydrogen delivery options over time

Based on the accumulated results as well as on more detailed investigations and stakeholder discussions, the following role of the transport options can be derived:

- Hydrogen production at the fuelling station (onsite) from natural gas or electricity is considered over the whole period studied, for areas where demand is too sparse for more centralised schemes. Practical limitations are the high space requirement (in densely populated areas), and the limited part-load ability of onsite SMR for fuelling stations with very low initial utilisation. Due to the low initial fuelling station utilisation assumed, and the cost increase of natural gas and electricity in later phases, on-site production has a relatively low share here. However, this is strongly sensitive to the ingoing assumptions and it can be stated that onsite production will in most scenarios be the supply mode of choice in certain locations.

- Tube trailer trucks delivering compressed gaseous hydrogen (CGH_2) have high variable costs (also per distance) due to the small amount of hydrogen they hold, but they are flexible and have comparatively low fixed costs. Under the current assumptions they appear to be an advantageous option for the shorter-distance transport and distribution of hydrogen within regions of intermediate density. In each studied scenario, the share of CGH_2 trucks is decreasing significantly over time, making them a technology for the transition to pipeline delivery.

- The delivery of liquid hydrogen (LH_2) by truck results in lower variable costs per distance due to considerably higher hydrogen capacity. However, the required large-scale liquefaction process implies high investments and variable costs. Due to the 20% LH_2 demand in the base case, LH_2 delivery dominates in the early phase when most fuelling stations only receive LH_2 and evaporate part of it to provide CGH_2. Dual supply of LH_2 and CGH_2 becomes more and more viable with growing turnover in later phases. The alternative scenarios (where no LH_2 is demanded at the fuelling station) show lower shares of trucked LH_2 in the early phases. Assuming higher fuelling station utilisation (alternative 2) has a positive influence on the share of this option. LH_2 truck delivery competes with onsite production for outlying fuelling stations with smaller demand. In urban centres, it competes with CGH_2 trucks and, later, pipeline delivery.

- Pipeline delivery implies high investments, but low variable costs. The investment scales linearly with delivery distance, while the dependence of capacity is weaker. Therefore pipelines are most economic at short distances or high turnover. For inter-regional transport from a central plant, the share of pipelines increases significantly throughout the period studied. Pipeline distribution is mainly an option for densely populated areas and larger fuelling stations. This indicates that distribution pipelines will become more attractive as hydrogen penetration advances further. A positive side effect of this is that their intrinsic storage capacity may facilitate the use of intermittent renewable energy sources.

It can be concluded that each of the transport options plays a role under specific conditions. The distance to be covered has the strongest impact on transport costs, which contribute a much higher share to the total supply costs of hydrogen than is the case for today's liquid fuels. The primary optimisation goal should therefore be to minimize the average hydrogen transport distances through well planned and distributed siting of the production plants.

CONCLUSIONS

In the HyWays project the optimisation of infrastructure build-up in 10 European countries is modelled, taking into account the specific viewpoints of industry partners and national stakeholders. The following conclusions can be drawn:

- Hydrogen infrastructure rollout will predominantly be initialised in densely populated areas. Drivers for the selection of such "seed points" are the commitment and political support in the regions, activities in research and development with the intention to ensure political support of the process and also visibility among interested individuals.

- The specific hydrogen costs in the early phase are high due to the required overcapacity of the supply and refuelling infrastructure and the higher initial costs for new technologies. However, the total economic impact of the early phase is small compared to later phases due to the comparatively low turnover, and the hydrogen costs already drop to 0.11-0.16 €/kWh in the second phase (500,000 vehicles in EU). A gradual build-up of the infrastructure with an initial concentration in agreed user centres thus efficiently diminishes the often cited chicken-and-egg problem.

- Assuming 20% of all hydrogen dispensed as LH_2, initially a high share of the hydrogen will be delivered by LH_2 trucks (with evaporation for CGH_2 demand). In later phases, gaseous hydrogen demand will gradually be supplied by pipeline transport and distribution, with CGH_2 truck distribution seen as a transition solution. The contribution of onsite production ranges from 5 to 12%, mainly in remote areas.

- Despite the high share of transport costs, more than half the hydrogen may come from centralised production combined with inter-regional transport in all phases. This underlines the fact that it is important to consider larger regions and the interconnections between them when aiming at an economically optimised build-up of hydrogen infrastructure. Well planned and distributed siting of the production plants is essential to minimise the transportation costs.

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