The Economics of a European Hydrogen Automotive Infrastructure

A study for

Linde AG

by

E4tech

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Final report

EXECUTIVE SUMMARY

Hydrogen could be put into widescale use as an automotive fuel to help address problems of pollution and security of energy supply. Developing an infrastructure to fuel the vehicles will be critical, and the economics of this are not well understood. This analysis uses an investment, cost and return model for a hydrogen infrastructure to support hydrogen car commercialisation in Europe. The timeframe of the study is 2010 to 2030, and data are taken both from existing studies and from original sources.

This study investigates the economics for two scenarios in which hydrogen infrastructure is built in selected European countries. One scenario considers infrastructure development based on urban areas with high population density, while the other looks at infrastructure developed around regions with strong automotive presence.

For simplicity, only hydrogen passenger cars are considered to provide the demand for this infrastructure, though in reality fleet vehicles will also play a part. Passenger cars could be in volume production around 2010, and gradually introduced from that point. Low and high uptake cases of the vehicles are modelled, with the resulting implications for hydrogen infrastructure development. Three different concepts of hydrogen supply are considered, including centralised and decentralised production paths.

The scenarios here are devised to assess the effect of several different variables on the financing of hydrogen infrastructure development. They are intended to allow the investigation of different parameters and are not predictions of what will happen. The study also does not attempt to find an optimum way of building hydrogen infrastructure, though some of the results indicate that a high degree of centralisation may be economically beneficial.

Under the scenario in which vehicles and supply infrastructure are allocated by population of urban areas, 40m vehicles are assumed to penetrate into the selected countries by 2030 in a high market uptake scenario, requiring 7Mt of hydrogen fuel. Building the 16,000 urban and 3,000 trunk road fuelling stations required to support these vehicles could cost as little as 6bn Euros with centralised production, or as much as 24bn Euros with on-site electrolysis at filling stations. In the case of the highest figure, the infrastructure investment can be approximated to 1bn Euros per annum across all European countries participating. For comparison with other infrastructure projects, the roll out of broadband to rural areas in Sweden cost 4.4bn Euros and the UK third generation mobile telephone licences were auctioned for approximately 35bn Euros.

Under the second scenario, vehicles are allocated to strategically chosen cities. In this case, the scenario is run until 2025 using the same base data, after which coverage is considered to increase organically across all countries. By 2025 some 20m vehicles have been introduced, with hydrogen demand of 3.5Mt, and a resulting total of 9,000 fuelling stations. Total cumulative investment in the different fuelling concepts is 3bn Euros in the lowest, and 9-12bn for the higher, distributed cases. In the lowest case, the total investment is 10bn Euros over the period 2010-2025, 6bn of which are in production plants.

The cashflows associated with these different scenarios suggest that positive results can be achieved in approximately ten years from initial investment on a straight line basis. This figure improves slightly in the second scenario, where more vehicles are concentrated into a smaller area, and hence the cost to serve each vehicle is lower. The cashflow varies between actors on the production side, where consistent positive results are obtained, and those who provide refuelling station infrastructure. In the latter case, net positive revenue streams depend heavily on the specific fuelling station concept under consideration. Centralised provision of hydrogen provides the best returns, while on-site production using reformers is less profitable, and on-site electrolysis has strongly negative returns. This is influenced by

underlying assumptions in the model and will certainly not be true for all regions or under all circumstances.

Both the comparatively low levels of investment and the cashflow figures are sufficient to suggest that they might fall within the horizons of major corporations. However, risk will need to be managed carefully as hydrogen vehicle uptake is a key uncertainty.

No explicit government support has been assumed, whether local or national. Possible mechanisms would include enhanced capital recovery factors, incentives for the purchase of hydrogen vehicles, zero emissions zones in cities, or other regulatory or market mechanisms. However, the selling price for hydrogen is set equivalent to the price of taxed gasoline on an energy basis, giving an implicit tax exemption for the period of the analysis. Equally, the gasoline price is assumed to remain constant over the period. Given the uncertainty associated with long-term energy prices, these factors should act to cancel each other out to some extent. In reality, once hydrogen has been successfully introduced into the market it seems highly unlikely that it would remain exempt from duty.

Government support is likely to be very important in minimising risk within all scenarios. Supportive and predictable policy frameworks will enable companies to make decisions on the basis of a known future – at least for some timeframe. Specific support for vehicles or infrastructure would provide greater incentives.

The different concepts for fuelling stations – fully centralised hydrogen production, or partially decentralised – have markedly different investment and revenue profiles. Within the limitations of the model it has not been possible to represent all local variables in fine detail, and so the electrolysis option, for example, appears to be quite unprofitable. This is due, in part, to high electricity prices in comparison with natural gas, and an assumption that final hydrogen selling prices are fixed and constant. In practice, local conditions will play a major part in an investment decision, and individual stations based on electrolytic production of hydrogen may be very attractive in some regions.

This analysis considers only the *economic* implications of developing a hydrogen infrastructure to supply passenger cars. Any future introduction of hydrogen will certainly be influenced heavily by policy, which will include both energy supply/resource considerations, and environmental implications, amongst other factors. None of these is modelled here, though CO_2 emissions from transport are currently a major consideration.

Although the costs of the scenarios are considerable, they are quite low in comparison with other infrastructure transitions and investments. A variety of actors could potentially participate in the development of such an infrastructure, including existing refiners and marketers of fuels, other forecourt operators such as supermarkets, and industrial hydrogen suppliers. Enough of these actors exist across Europe for the risk to be shared as required.

In summary, it appears that the costs and returns associated with developing an initial hydrogen infrastructure are not obviously prohibitive. A significant fleet of passenger cars could be supported in 19 European countries for approximately the same cost as the mobile phone network licences auctioned in the UK in 2000. Although the undertaking may be potentially both expensive and risky, this is a typical characteristic of previous energy and infrastructure transitions.

Given the considerable business risk involved in such an undertaking, a supportive policy framework and the fit of the risk with individual corporate strategies will be essential. The development of the infrastructure in a suitably co-ordinated fashion – concentrating on aggregated demand centres – could potentially allow more rapid payback and also minimise some of the risks.

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1 INTRODUCTION

The use of hydrogen as a widespread vehicle fuel is attracting significant interest within major corporations and with senior politicians. The potential benefits in pollution reduction and energy security have attracted substantial investment. Nevertheless, the transition to hydrogen is complex, and demands not only new technologies that can replace existing tried-and-tested ones, but also political will and public desire. A key part of the change will be developing the infrastructure – rapidly enough to provide vehicle fuel where the customer demands it, but slowly enough to enable some profit to be made by the investing parties.

While some studies have been undertaken to investigate hydrogen infrastructure costs, few have examined the investment requirements that will need to be addressed if such an infrastructure is to be financed. This study, commissioned from E4tech by Linde AG, considers two possible ways in which an infrastructure might be developed within Europe, and looks at the financial implications of each. The costs can be seen to be well within the bounds of previous transitions, some of which share similar characteristics to a hydrogen energy transition.

1.1 Background to the study

Many studies of hydrogen infrastructure already exist, and consider technical, economic, social and environmental issues associated with the development of hydrogen provision for vehicles (see bibliography). However, relatively few address the issues associated with financing that infrastructure. While costs are increasingly provided, they tend to be aggregated over a total infrastructure in a country or region, with little indication of which actors might be prepared to take the risks necessary to finance the development, over what timeframes, or what support may be required. As a result, they can sometimes appear to be strikingly large.

While this study is far from being a full financial analysis, it provides an initial estimate for the costs of providing a refuelling infrastructure for hydrogen vehicles in parts of Europe, coupled with cashflows over the period of the investigation – from 2010 until 2030. In this way the possible costs and rewards arising from such an infrastructure can be assessed, to establish the likelihood of companies, countries or other actors being prepared to make such an investment. The infrastructure development is then put into the context of previous similar undertakings.

This report discusses the results of a modelling analysis of two potential infrastructure development scenarios, and the results of those scenarios under different conditions – high and low hydrogen vehicle penetration, and different types of hydrogen provision. It is essential to note that this study does not attempt to predict what may happen, nor to select an ideal route for hydrogen infrastructure development, but to put forward scenarios for discussion and further analysis. The study is also incomplete inasmuch as it does not consider the social or environmental implications of such infrastructure development – this type of analysis is ongoing for Europe within other projects, for example the EU-funded *HyWays*[1].

The two scenarios analysed are chosen to give two perspectives on infrastructure development. The first simply selects areas of high population density in certain European countries and allocates vehicles – and then infrastructure – to them. The second considers more of the real-world issues likely to affect geographical uptake of hydrogen, and uses both different cities and linking roads, partly based on the location of automotive suppliers.

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[1] See www.hyways.de

The study attempts to give a perspective on how a fully-functional infrastructure may be developed, once vehicles and supporting technologies have been tested to the satisfaction of the companies involved. In early 2005, several hundred cars already exist or are being introduced into projects world-wide, and seventy fuelling stations have been built. However, these are still demonstrations and bigger steps must be taken to enable the scenarios presented here. The linking of existing fuelling stations by 'filling in the gaps' between them so that current hydrogen vehicles can travel outside their current limited space, and the introduction of more vehicles under different conditions, are essential to provide the groundwork for production versions of both cars and infrastructure.

1.2 Objectives

The primary objective of the study is to develop a cost model for the development of a hydrogen refuelling infrastructure in Europe, based on defensible assumptions, to answer two questions:

- How much might a hydrogen refuelling infrastructure for vehicles in Europe cost?
- What actors might invest in this infrastructure, and for what reward?

The first of these questions can be answered in a comparatively straightforward manner by the development of a suitable model, while the second is more subjective. The object of this analysis is not to specify the individual companies that may invest, but to identify types of actors in the energy chain with an attitude to risk and reward that may fit with the model results.

1.3 Assumptions

In order to produce a model to investigate the questions above, it has been necessary to make a wide range of assumptions. These come about because of a lack of data, uncertainty regarding the future, or to ensure that the model is manageable. A more complete list is given in the Appendices, but key assumptions are explained below. Several assumptions, including those regarding fuel consumption and pricing of hydrogen, are based on the existing *HyNet*[2] work supported by the EU.

Hydrogen demand is assumed to come from hydrogen cars sold into the consumer market. The issue of demand leading supply is crucial in solving the real problems of investment risk in such a new supply infrastructure, but the purpose of this analysis is to investigate infrastructure costs, so we have chosen to treat demand as an exogenous variable. We have used penetration scenarios for the period 2010-2030 from the ongoing EU *HyWays* project. Although no scenario should ever be confused with a prediction, these have been discussed amongst the many partners of the project and some level of consensus achieved.

These vehicle penetration scenarios are based on passenger car numbers and assume that hydrogen vehicles will begin to enter volume production in 2012. The first vehicles sold appear in the data below in 2013. This is consistent with several of the automotive manufacturers who suggest that they will have vehicles ready in the 2008-2012 timeframe. In advance of vehicles being supplied to showrooms, significant preparatory steps must be taken, and so the period from 2005 onwards is essential. These steps include the full development of infrastructure components such as fuel dispensers and storage tanks; the technical refinement and subsequent demonstration of many hundreds of hydrogen vehicles and refuelling stations able to supply them; and the introduction of suitably supportive codes, standards and policies. Although the data do not show vehicle penetration in 2010, in reality some 500 hydrogen

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[2] http://www.hynet.info/

vehicles exist worldwide to date[3], and this number will be added to in the years up to the start of this model.

Hydrogen vehicles are assumed to be available only in certain areas initially, enabling development of an infrastructure in certain demand clusters, rather than a very widespread but locally very small uptake. Details of this assumption can be found under the different scenarios. The vehicles are not included in any of the cost calculations, as we have assumed that the vehicle manufacturers will bear the investment risk, costs and revenues as they do today.

Infrastructure investment is assumed to lead demand by three years for the duration of the study – i.e. that it will take three years to finance, build, commission and begin to run the relevant plant. This is a conservative assumption – much of the infrastructure could be built more quickly – but also takes into account to some extent the issue of sufficient provision of hydrogen fuelling stations for customers' comfort in refuelling. It has not been possible to find a definitive indication of the penetration of infrastructure required for customers not to feel restricted, so we have taken a cautious view. Ongoing development of technology such as GPS systems and telematics should enable refuelling stations to easily be found in the future.

Penetration of vehicles – and hence infrastructure – is broken down into phases, in which different cities, countries and link roads are considered. This is a simplification of a fully organic growth of infrastructure in which a hydrogen fuelling station may be built at any location at any time. The assumption is made as it is considered highly likely that roll-out of vehicles and infrastructure will take place in such a co-ordinated fashion, to avoid resources being spread thinly over a wide area.

The urban areas chosen for vehicle sales are done so on the partially arbitrary basis of population, or proximity to automotive suppliers, and do not take into consideration potentially crucial factors such as local fiscal regimes, policy incentives, location of vehicle production plants or similar.

2 EXISTING STUDIES

While not all studies are public, the bibliography in Appendix 11 lists many other studies that investigate, or touch on, hydrogen infrastructure development. The list is not exhaustive. These studies have been conducted by a wide range of organisations, in different geographical locations and using different assumptions. Different questions have been asked, and results vary according to these factors. This study is intended neither as a critique nor replacement of the different studies, and in fact builds on methods or data from several of them. The majority of the studies so far undertaken are US-based, with others in Canada and in Europe. Japan has also some detailed analysis in the area, though this is less accessible for non-Japanese speakers.

In terms of infrastructure *investment*, comparatively little comprehensive work is publicly available. Some very detailed reports have been produced (e.g. Thomas, Ogden, LBST, Melaina etc), but most concentrate on infrastructure costs, without touching on the actors who may invest. Given the uncertainties associated with infrastructure investment, no model will provide more than a first order insight to the problem, but an indication of the flow of costs and revenues associated with such a development gives a valuable perspective on who may be able to afford such investments, and what timing or support may be required.

Original and real-world data are scarce for hydrogen technologies, particularly as many are still under development. Many studies therefore rely on data from previous studies but analysed in a different way. Some, of course, have original sources. Additionally, technology characterisation within the studies is either 'as-is' – today's known and typically large-scale

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[3] Source: Fuel Cell Today www.fuelcelltoday.com

equipment, or ‘future-potential’ – as projected by learning curve or engineering studies. Little new technology development is or can be specifically included, as it is frequently either under confidentiality agreements or limited robust data are available.

More specialised studies are beginning to emerge as analysis of potential hydrogen transitions becomes more sophisticated. Some studies display innovative approaches in terms of maximising hydrogen output, reducing inefficiency or flattening costs. Often these involve quite complex integrated systems where stationary energy and/or transport fuel may be produced, and some discussion of flexible markets is considered. Liberalised energy market issues will clearly have a large impact on future infrastructure development.

This study should be read in the context of other analyses and in the context of external factors influencing hydrogen infrastructure development in different regions.

3 INTRODUCTION TO THE MODEL

The model here has been developed as a stand-alone tool for investigating costs and revenues associated with the different components for a hydrogen infrastructure, both individually and in aggregation. The development of the infrastructure itself will be strongly dependent on local conditions, and geography will play a part. However, it is not possible to represent all of these issues in this model, and so a spatial dimension has not been analysed in detail. However, higher fuelling station density than would be provided simply to meet demand is allowed for in the early stages of development.

3.1 Purpose

The aim of developing the model is to assist with answering some of the questions that surround the development of a future hydrogen refuelling infrastructure. These include the amount of hydrogen that will be required for a vehicle fleet, the magnitude of costs associated with its production, distribution and transport, cashflows for different possible actors over the time periods under consideration, and the magnitude of investments in different countries. The model is not intended to predict how an infrastructure might develop, nor assess the optimum configuration or speed of development, as many local variables must be considered in each case. However, the model does compare some indicative examples of hydrogen infrastructure.

3.2 Methodology

The development of the model is based on two primary inputs or assumptions. The first is the demand provided by the HyWays project (Figure 8); the second is a list of major urban areas agreed at the start of the project and included as Appendix 1. Development of the infrastructure then takes place in different phases, according to two different scenarios.

The first (population) scenario is entirely based on population density, and is developed around major urban areas in Europe, as shown in Figure 1 to Figure 4. Infrastructure is added in four phases of five years, in which urban areas are added in groups and linked by main roads. Areas in green have hydrogen infrastructure developed during that phase, while cities in red will be included in later phases of hydrogen infrastructure development. The size of the circle approximates the population of the urban area.

The second (strategic) scenario is designed to investigate an alternative approach. This takes into account to some extent the strength of certain industrial areas in hydrogen energy, and the location of automotive industry. In this case the first phase is a development linking existing hydrogen fuelling stations in Germany and adding some further locations, followed by a phase in which nearby urban areas are also linked, and a third phase in which the infrastructure is extended further. In this example phase 1 is shown in red, phase 2 in blue, and phase 3 in green (Figure 5 to Figure 7). The penetration of vehicles is thus allocated to a more concentrated geographical area in this second scenario. This scenario assumes that phase 4 will be a full roll-out of infrastructure to cities across Europe, and is not shown in the modelling. The analysis therefore runs until 2025.

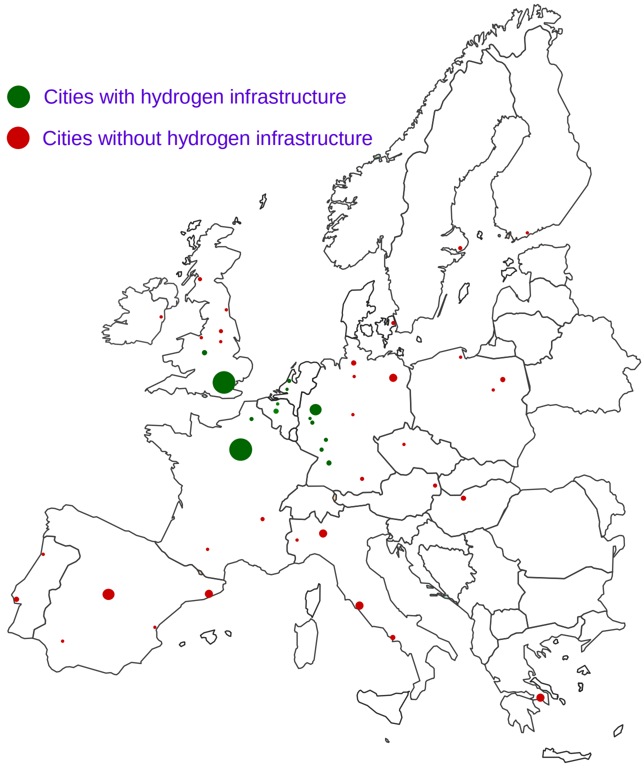


Figure 1: Scenario 1, stage 1 – cities where the first hydrogen infrastructure is installed

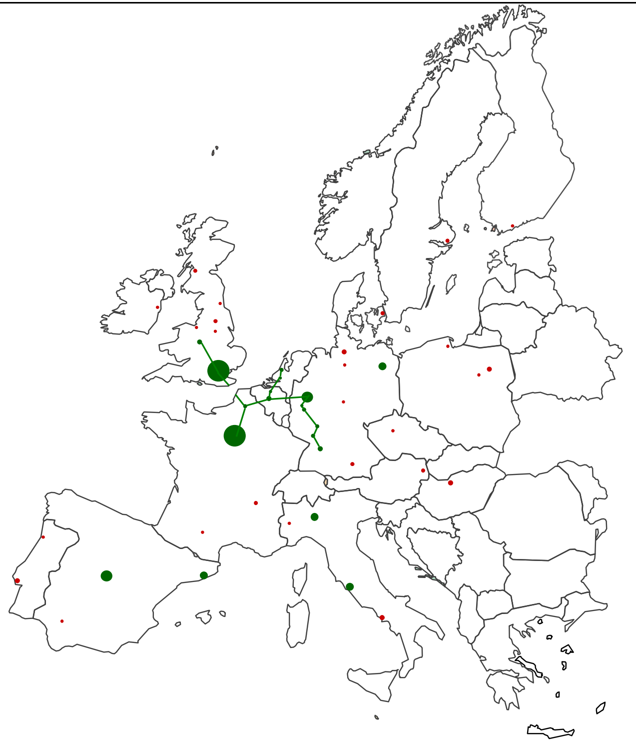


Figure 2: Scenario 1, stage 2 – installing hydrogen infrastructure in new cities and developing trunk road links between existing cities

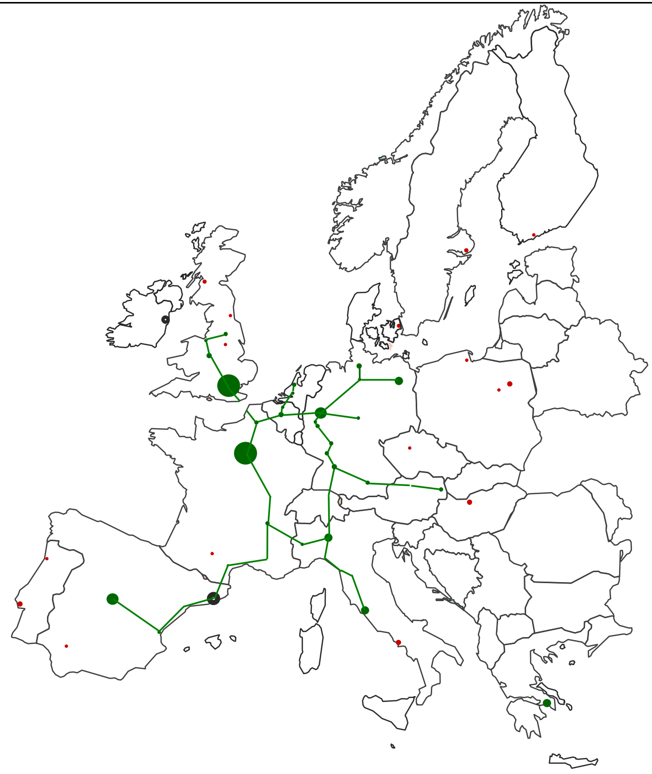


Figure 3: Scenario 1, stage 3 – adding further cities and developing more trunk road links

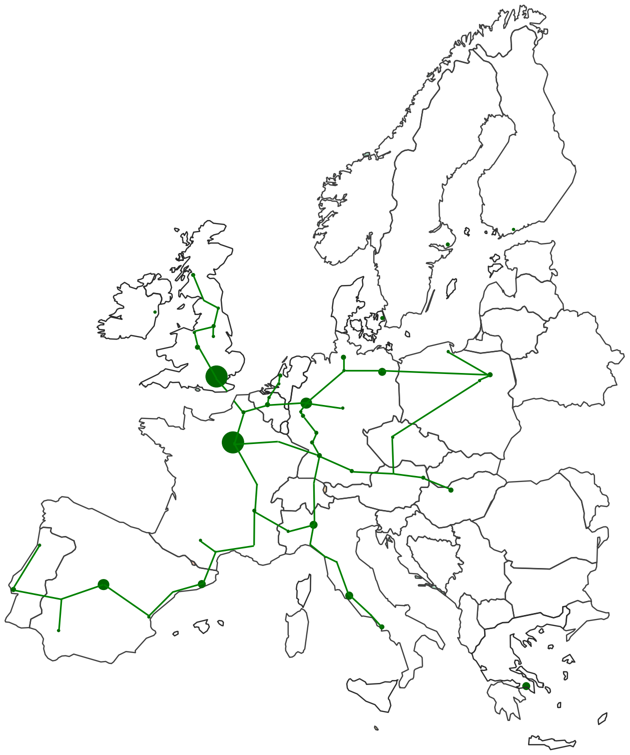


Figure 4: Scenario 1, stage 4 – integrating more cities into the infrastructure

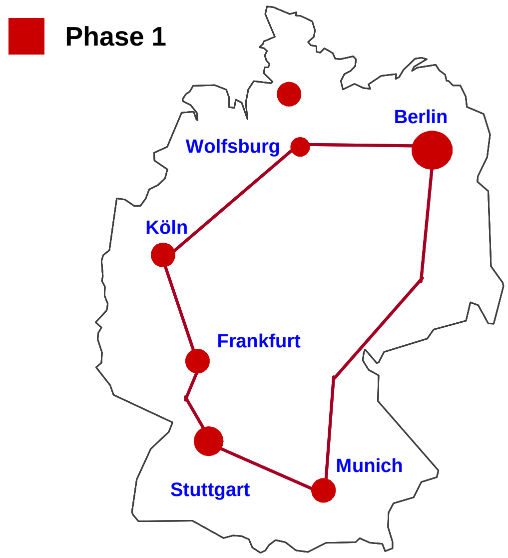


Figure 5: Scenario 2, stage 1 – linking existing infrastructure

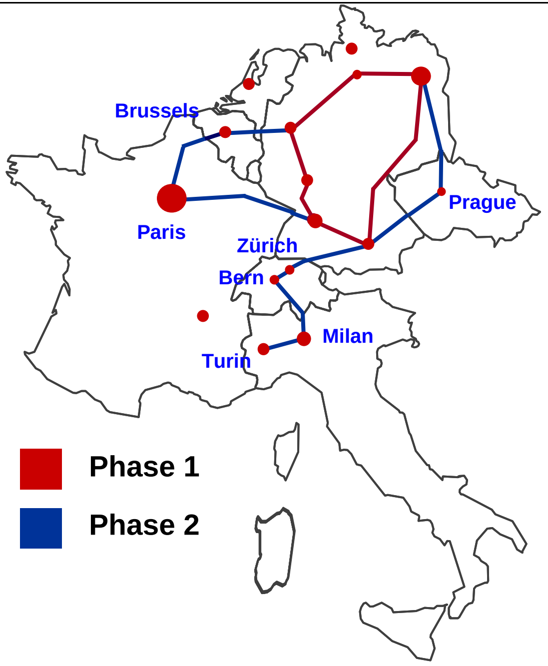


Figure 6: Scenario 2, stage 2 – adding nearby cities

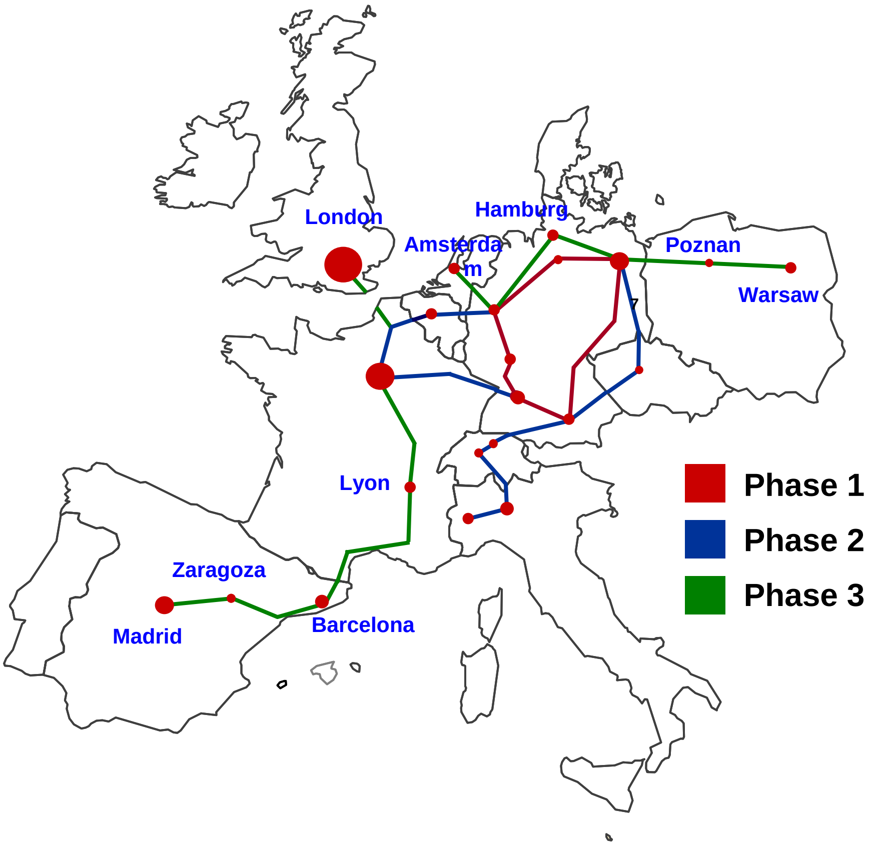


Figure 7: Scenario 2, stage 3 – linking to more distant cities

Cars

For each of the two scenarios the method of allocating vehicles is similar. For each urban area, the total passenger car fleet is derived from the number of inhabitants for the area using data from the Wikipedia Encyclopedia and number of passenger cars per inhabitant for that country from Eurostat. No correction is made for any difference between urban and rural car ownership.

Additional hydrogen cars are introduced year after year – high and low cases are considered as shown in Figure 8, with 4 types of hydrogen vehicles (ICE only, ICE hybrid, FC only, FC hybrid). Initially the share of vehicles is divided equally between ICEs and FCs, but fuel cell vehicles are considered to become a greater proportion of vehicles sold over time. Vehicles are considered to have a ten year lifetime.

Although the total number of hydrogen vehicles for Europe is given by *HyWays*, in this model they are allocated proportionally across the different countries for a given year. This allocation is based on the total vehicle fleet of each city with a hydrogen infrastructure in that given year. Figure 8 shows the total penetration across the EU for scenario 1. Scenario 2 follows the same curve, but is only modelled until 2025. Tables can be found in Appendix 13.

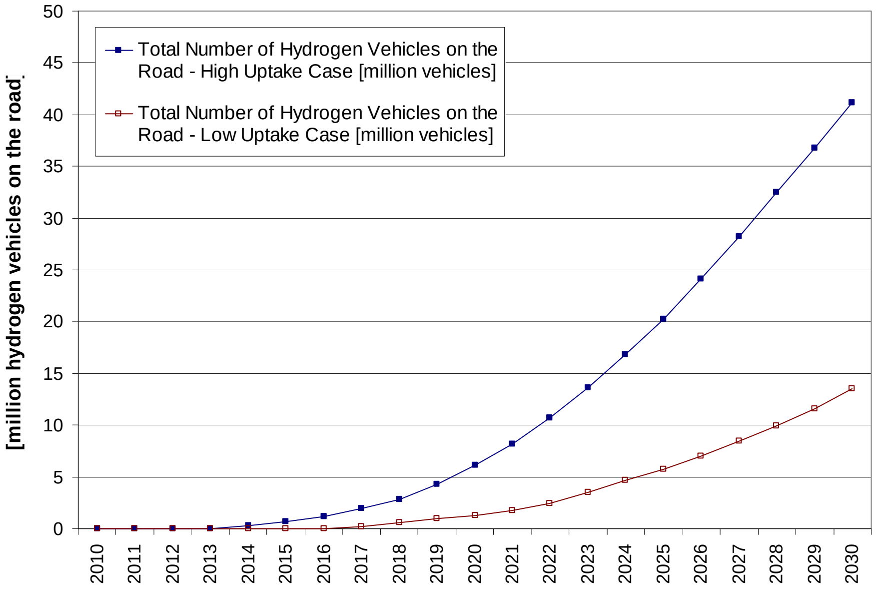


Figure 8: Penetration scenarios for hydrogen vehicles in Europe

Figure 9 shows the same data, expressed as an equivalent percentage of the fleet in the EU15. This also gives some indication of the proportion of hydrogen fuel sales for the different cases.

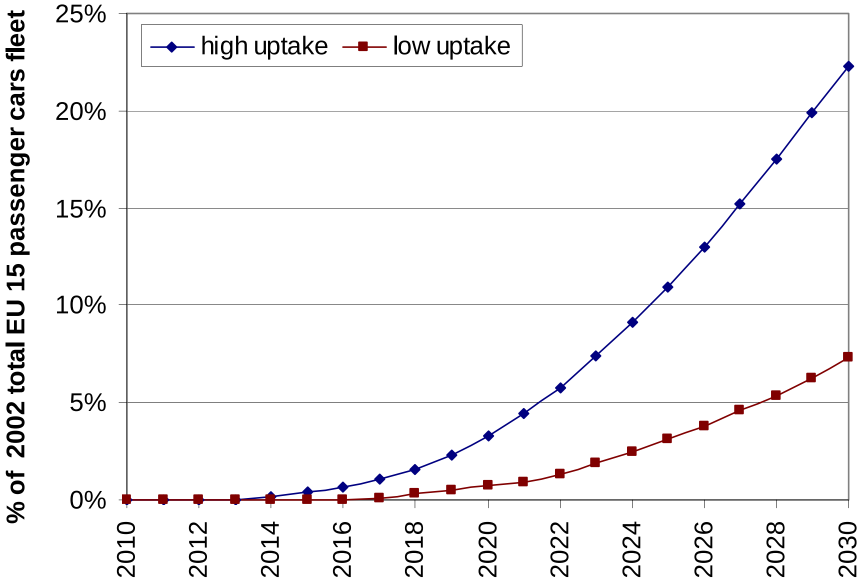


Figure 9: Penetration of hydrogen vehicles in Europe, given as a percentage of the 2002 fleet

Hydrogen vehicle fuel economy is kept constant over the period to 2030 at 4 kgH_2 per 500 km for fuel cell vehicles and 7 kgH_2 for internal combustion-engined cars. The average fuel economy of the fleet improves over the period due to the evolution of the share of the different types of vehicles. The average distance travelled each year by a passenger car is taken to be constant over the period, at 15,000 km for all countries.

Industrial 'surplus' hydrogen is considered to be available on the market. This is kept constant over the period at 2% of total 2004 European hydrogen production of 8 million tonnes, or 160 thousand tonnes. Allocation of this surplus hydrogen for a given year is based on the total vehicle fleet in cities with a hydrogen infrastructure in that year.

The number of urban fuelling stations required is based on meeting projected demand, with a standard refuelling station unit capacity of 12,000Nm^3 per day for the high uptake case, and 7,000Nm^3 per day for the low. This ensures that sufficient capacity is in place to provide fuel, while the total number of fuelling stations does not exceed that already in existence. The numbers are derived from analysis of the capacity required to fuel a representative number of vehicles. In order to take into account a requirement to build excess infrastructure initially, an 'amplifying factor' is used, which decreases over time. In the first year this is set very high at 30 (i.e. if demand can be fully met by one station, 30 are built); it decreases rapidly as more fuelling stations become equipped with hydrogen.

Roads

Fuelling stations are also placed on trunk roads linking the urban areas with hydrogen requirements. The number of fuelling stations is based on a proportion of the traffic of each road, with the same standard unit capacity than for urban stations. 3 levels of traffic flow are assumed based on data from the ESPON programme: 10,000, 50,000, and 100,000 vehicles per day. Each hydrogen vehicle travelling on a trunk road is given the chance to refuel its tank once.

Costs

The initial investment cost of fuelling stations is a function of the concept chosen (3 concepts are used, defined in section 3.3); initial investment cost is based on Linde data for a 7,000 Nm^3 per day fuelling station, and on the ratio between the actual capacity and the reference capacity.

The investment cost for a fuelling station decreases with the total number of fuelling stations installed. This total is assumed to be the number in the EU multiplied by three, to take into account world wide developments. The cost function is shown in Figure 10.

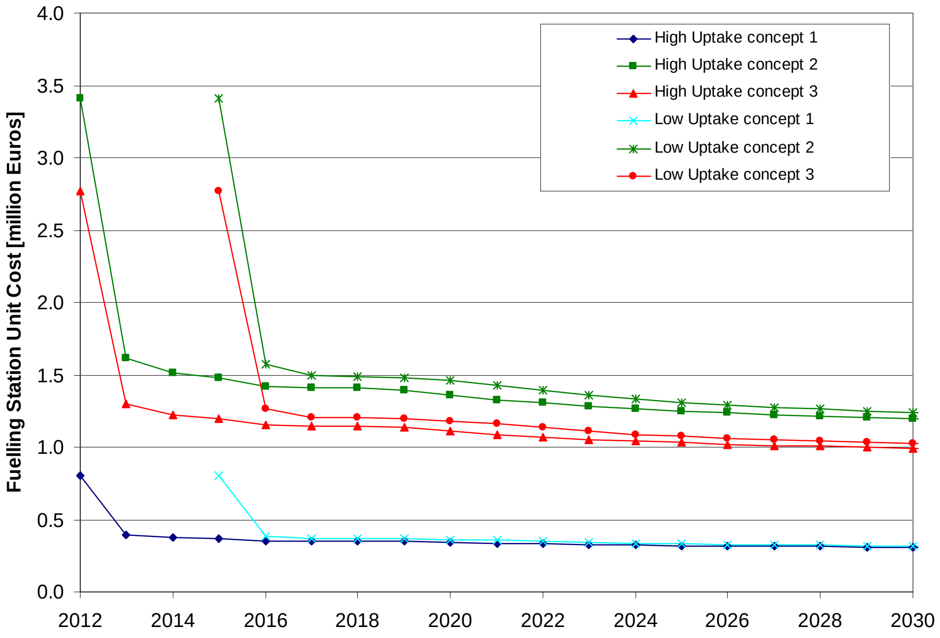


Figure 10: Reduction of unit production equipment cost with increasing volume of components produced

Initial investment costs for production and liquefaction plants as a function of unit capacity are based on data from Linde. The number of plants required by a given country is derived from the respective hydrogen demands of its urban areas plus trunk roads, minus any allocated hydrogen surplus on the market. No inter-country trading is assumed. However, excess hydrogen produced by plants initially over-sized (to cope with future demand) is considered to be sold on the industrial market. These plants operate at a minimum of 50% capacity and sell only the proportion of hydrogen up to that capacity rating that is not used to fuel vehicles.

The investment cost for production plants also decreases with the total number of plants installed, in the same way as for fuelling stations. The initial investment costs for delivery trucks as a function of unit capacity are based on data from Linde, and the number of trucks required by country derived from respective hydrogen demands. Once again, the investment cost of delivery trucks decreases with the total number of trucks, in the same way as above.

The operating costs for production and liquefaction of hydrogen are based on a Linde study in the context of Germany, while operating costs in other countries are based on the same reference but with correcting factors applied. These take into account the ratio between natural gas and electricity prices in Germany and the other country. The same is true for operating costs for fuelling stations, which are based on a Linde study in the context of Germany with correcting factors taking into account electricity price ratios. An indication of the difference in costs by country is given in Figure 11, in which it can be seen that operating costs can vary by 30% in different areas.

Transport costs are based on a Linde study in the context of Germany, and increase with the unit capacity of the production plants. This is because a greater number of smaller plants is required for a given hydrogen demand, and they can therefore be closer to demand points.

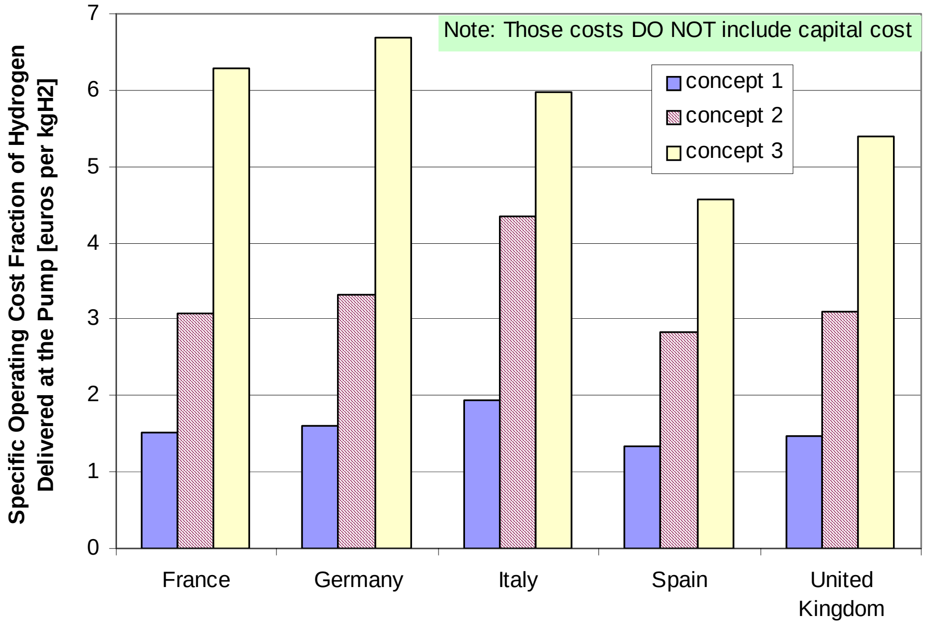


Figure 11: Different operating costs for hydrogen production concepts in selected EU countries

The selling price of hydrogen to the consumer is based on the current sale price of gasoline, tax included. For the purposes of the model, hydrogen is not assumed to be taxed. It appears that this will be important during the initial years, though it may be possible to levy a tax in the future to ensure revenue neutrality, once the infrastructure is sufficiently developed and demand entrenched. This is counterbalanced, to some extent, because the gasoline price is kept constant throughout the period. The different selling prices, based on equivalence with gasoline in 2003, are shown in Figure 12.

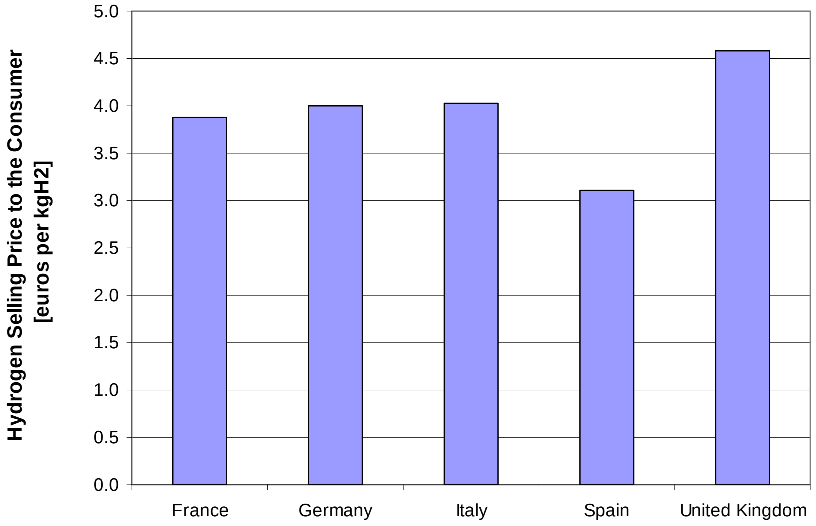


Figure 12: Hydrogen selling price for selected countries, proportional to taxed gasoline

Cashflows are then calculated for the production and transport actors, and subsequently for the distribution actors, in each country. The number of actors on the production/transport side is set to 2 in every country as an indication of who might enter the market – an energy company or industrial gas supplier – while the number of actors on the distribution side is set to 3 in every country. This is considered quite a conservative estimate of those that might enter the refuelling market, and could represent energy companies or major supermarkets.

The undiscounted cumulated cashflows for production/transport side actors are produced from the investment in production and liquefaction plants, the investment in delivery trucks, the cost of any hydrogen bought from industrial surplus, the costs related to operation and maintenance of production and liquefaction plants, the transport costs, revenues from hydrogen sales to the hydrogen distributors, and the revenues from the sales of excess hydrogen to the industrial sector. A 10% discount rate is used for the discounted cumulated cashflows.

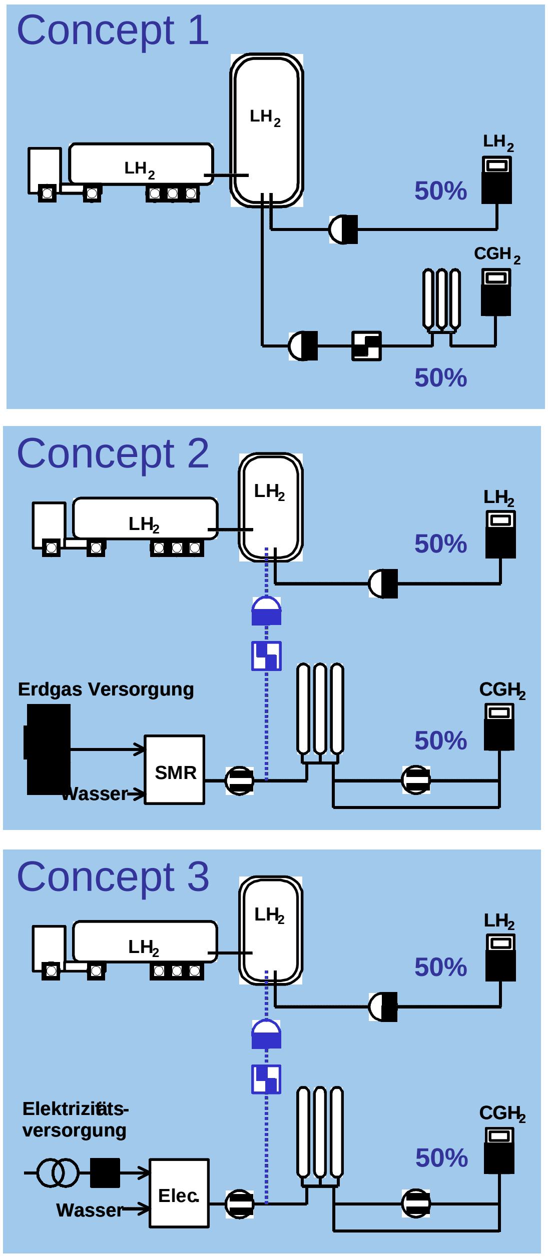
The undiscounted cumulated cashflows for the distribution side actors result from the investment in fuelling stations, the cost of hydrogen bought from the hydrogen supplier, the expenses related to operation and maintenance of fuelling stations, and revenues from the sales to the final consumers. Again, the discounted cumulated cashflows assume a 10% discount rate.

3.3 Hydrogen supply pathways chosen

Three hydrogen supply pathways have been chosen as representative of possible futures. These consider centralised production of hydrogen, and on-site production at the refuelling station using small-scale reformers or electrolysis. Clearly, the adoption of different options in different regions will be driven by a number of local factors, including the ratio of gas to electricity prices, distances from hydrogen production plant to fuelling stations, and indigenous company strengths. Local policy initiatives will play a potentially crucial role. These three simplified options are considered to give an indication of the possible variations.

- Concept 1 is entirely centrally-based, with hydrogen produced by large-scale steam-methane reformers and liquefied, before being delivered to the fuelling stations by tanker. Half of this is in the form of gaseous hydrogen, the rest in the form of liquid hydrogen. Gaseous hydrogen is then supplied to the vehicles.
- Concept 2 includes half of the hydrogen provided as in Concept 1, but relies on small-scale on-site steam reformers to provide the remainder.
- Concept 3 is similar to Concept 2, but electrolysers are used in place of steam reformers.

The Concepts are illustrated in Figure 13



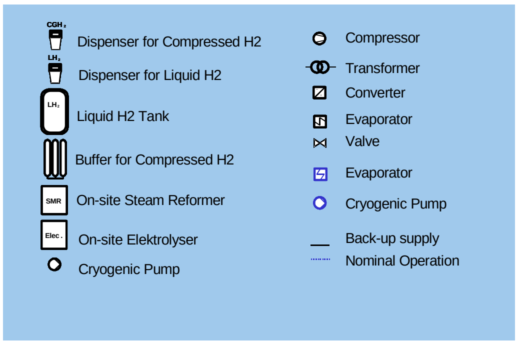


Figure 13: The 3 different hydrogen production and supply concepts

4 RESULTS

Results of the analysis are presented in this main body of the report. However, the range of scenarios and cases analysed has produced a very large amount of data, and so much of this is presented in appendices at the end of the report. In this section we concentrate primarily on scenarios 1 and 2 under high penetration of vehicles, though in some cases the low penetration figures are given for comparison.

4.1 Scenario 1

As stated, the primary driver of each scenario is the number of hydrogen vehicles in the European fleet. Figure 14 shows the penetration of hydrogen vehicles from 2010, when small but fundamentally important demonstrations and fleet developments are underway, to 2030, when millions of hydrogen vehicles are on the roads, and the corresponding increase in the volume of hydrogen required. High and low penetration cases are analysed. As can be seen, growth is rapid and shows no signs of slowing over this period. By 2030, in the high penetration case, over 40m vehicles have been put onto European roads, and about 7Mt of hydrogen is required to fuel them.

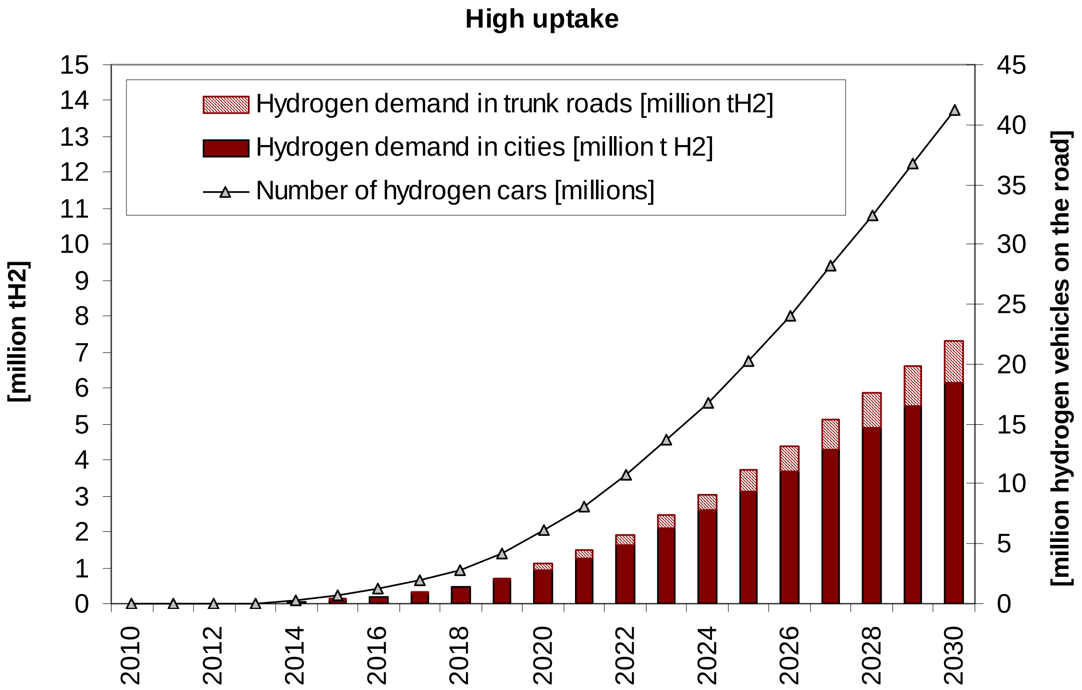


Figure 14: Hydrogen vehicle uptake and corresponding hydrogen demand to 2030, high uptake case

The low uptake case is shown in Figure 15, where close to 15m hydrogen vehicles are in place in 2030, requiring over 2Mt hydrogen.

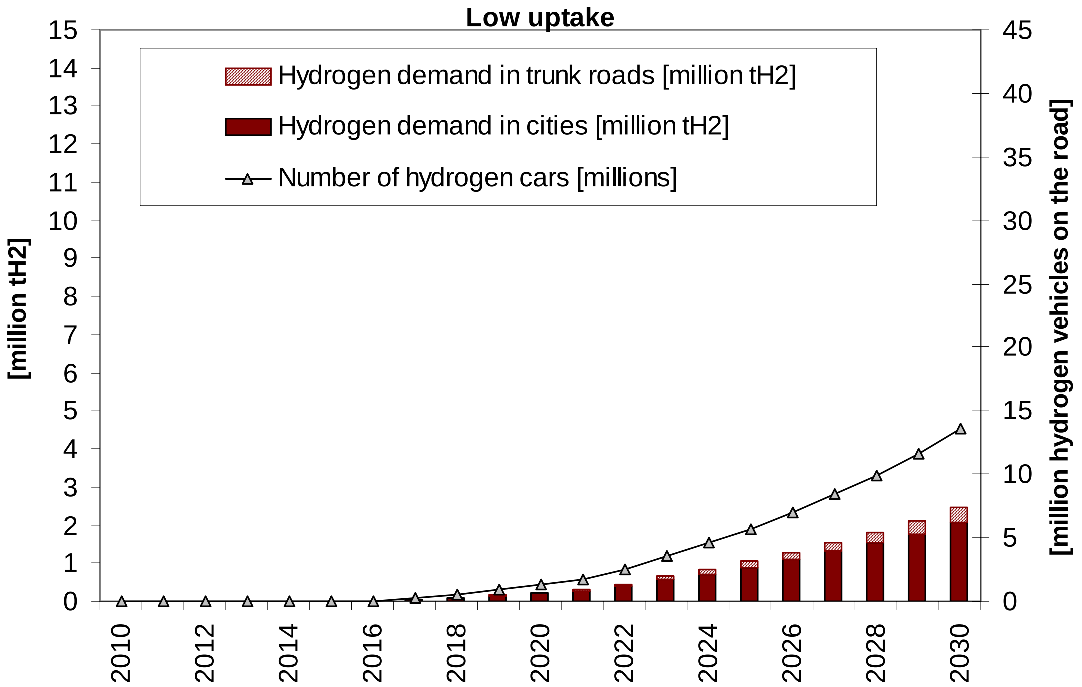


Figure 15: Hydrogen vehicle uptake and corresponding hydrogen demand to 2030, low uptake case

A breakdown of the demand between urban areas, and the trunk roads linking them, is shown in Figure 16. The urban areas dominate, as may be expected.

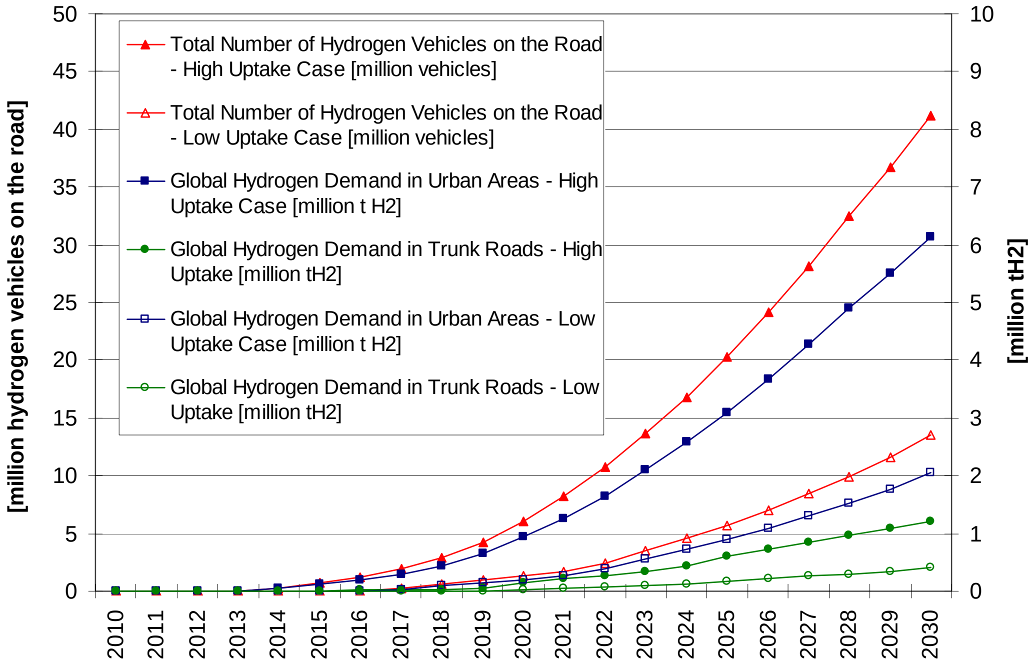


Figure 16: Hydrogen demand for urban and trunk road fuelling stations to 2030, scenario 1, high and low uptake

4.2 Vehicle penetration by country

Figure 17 and Figure 18 below indicate how vehicle uptake progresses by country according to the different scenarios. The vehicles are distributed within the urban areas considered in proportion to the population density of the region. In the high penetration scenario, by 2030 Germany has close to 12m hydrogen vehicles on the road, while the UK has about 8m, and France 6m.

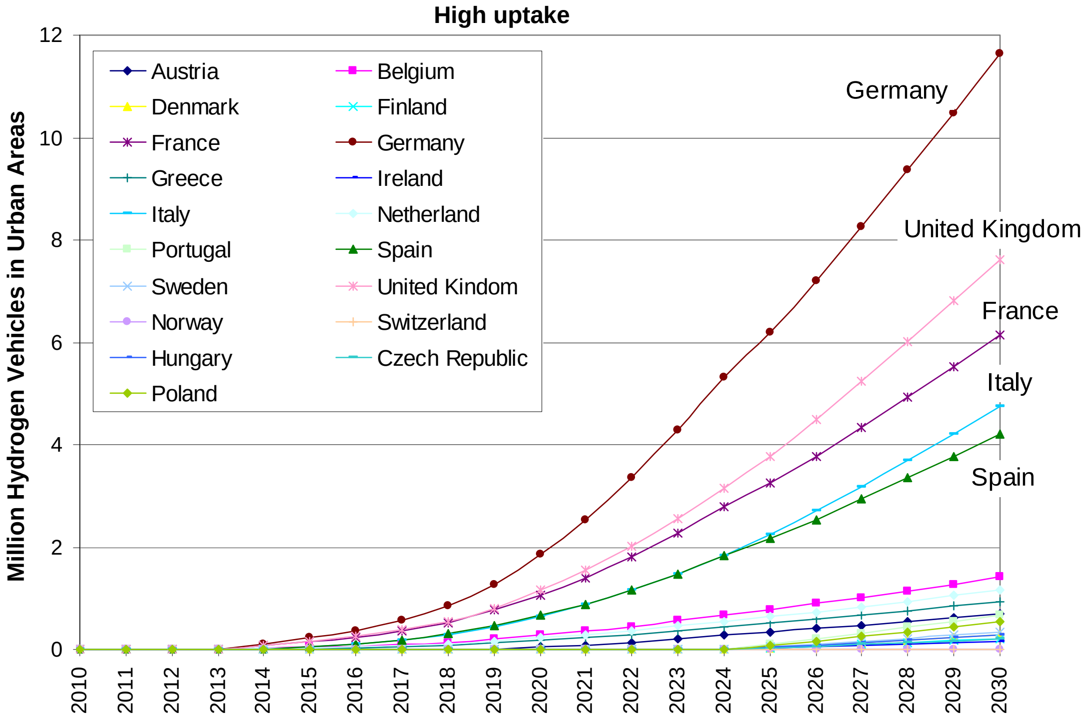


Figure 17: Hydrogen vehicle uptake by country, scenario 1, high uptake

Under the low penetration scenario, the figures are reduced by about two-thirds, with some 4m vehicles on the road in Germany.

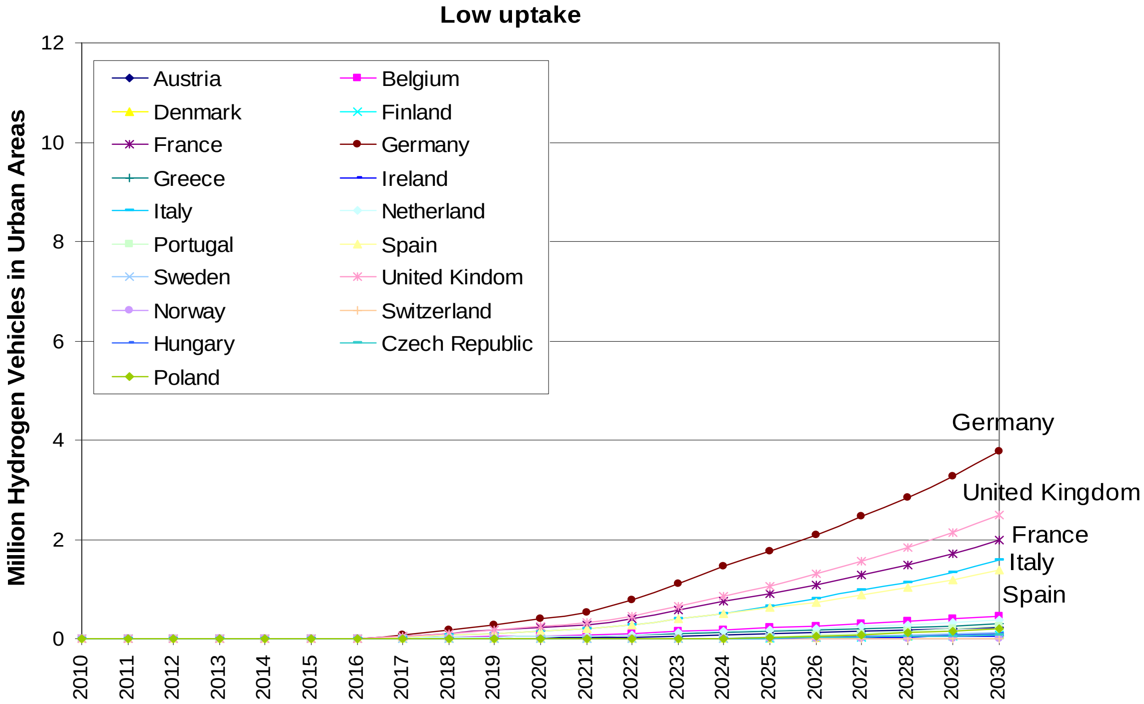
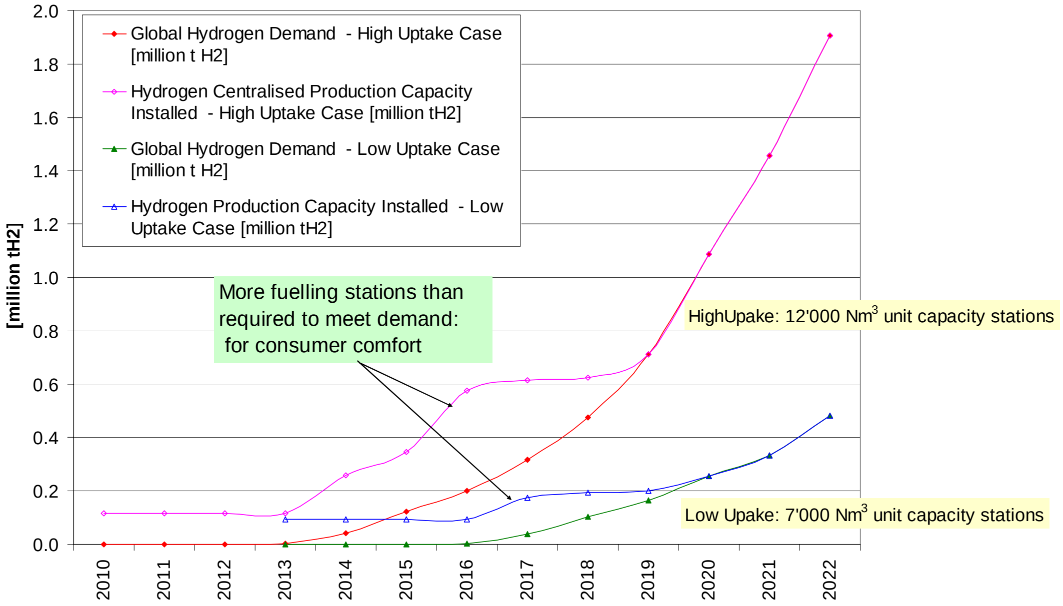


Figure 18: Hydrogen vehicle uptake by country, scenario 1, low uptake

In order to meet customer requirements for comfort – several refuelling stations close by – the initial stages of the infrastructure development have more fuelling stations than required for the amount of hydrogen demanded. This is indicated by the gap between capacity and supply in the early years. Figure 19 shows the resultant installed hydrogen production capacity, and the demand. The two different penetration rates have different filling station sizes ascribed to them, in order to meet demand without a requirement for a very large number of stations. This is clearly a simplification – fuelling stations of different sizes will be in place – but gives a useful approximation for the purposes of the study.



More fuelling stations than required to meet demand: for consumer comfort

HighUpake: 12'000 Nm^3 unit capacity stations

Low Upake: 7'000 Nm^3 unit capacity stations

Figure 19: Hydrogen demand and installed production capacity in early period of uptake, scenario 1

4.3 Fuelling stations by country

For the high penetration case, nearly 16,000 fuelling stations providing hydrogen are required in urban areas in 2030 (Figure 20). Each station is capable of delivering 12,000 Nm^3 of hydrogen per day. Just over 3,000 stations are needed on the trunk roads linking those areas. The cumulative investment for the former case over that period varies according to the refuelling concepts considered, but is around 6bn Euros for the case in which liquid hydrogen is delivered (production costs are concentrated upstream), and between 19 and 24bn Euros for the cases where half of the production is on-site at the fuelling station. In the case of the highest figure, the infrastructure investment can be approximated to 1bn Euros per annum across all European countries participating. The number of fuelling stations shown implies an equivalent of 28 stations per 100,000 cars of the *current* total fleet in the urban areas considered.

Figure 21 gives the same data for the low penetration scenario. This implies 16 stations per 100,000 cars.

Although Figure 20 and Figure 21 show the numbers of fuelling stations and the associated investment occurring in the same year, the model assumes a three-year lead time for all infrastructure. This conservative assumption allows for delays in project development and also enables the number of fuelling stations providing hydrogen to remain slightly higher than demand, to assist in providing consumer confidence. The implications for cashflow are shown later in the report.

Costs for the different concepts are significantly different due to the allocation of production costs to the fuelling stations for the on-site concepts. This effectively moves the cost – and risk – to a different actor in the fuel chain. Total investment costs for the infrastructure are compared subsequently.

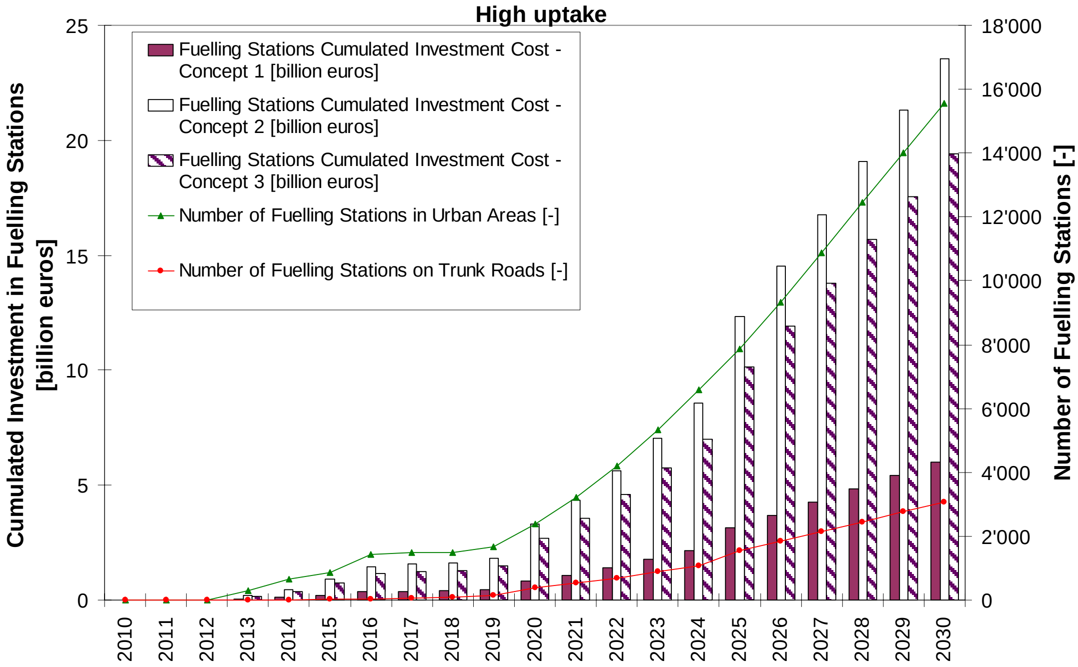


Figure 20: Number of fuelling stations and associated investment cost for high uptake and different fuelling concepts, scenario 1

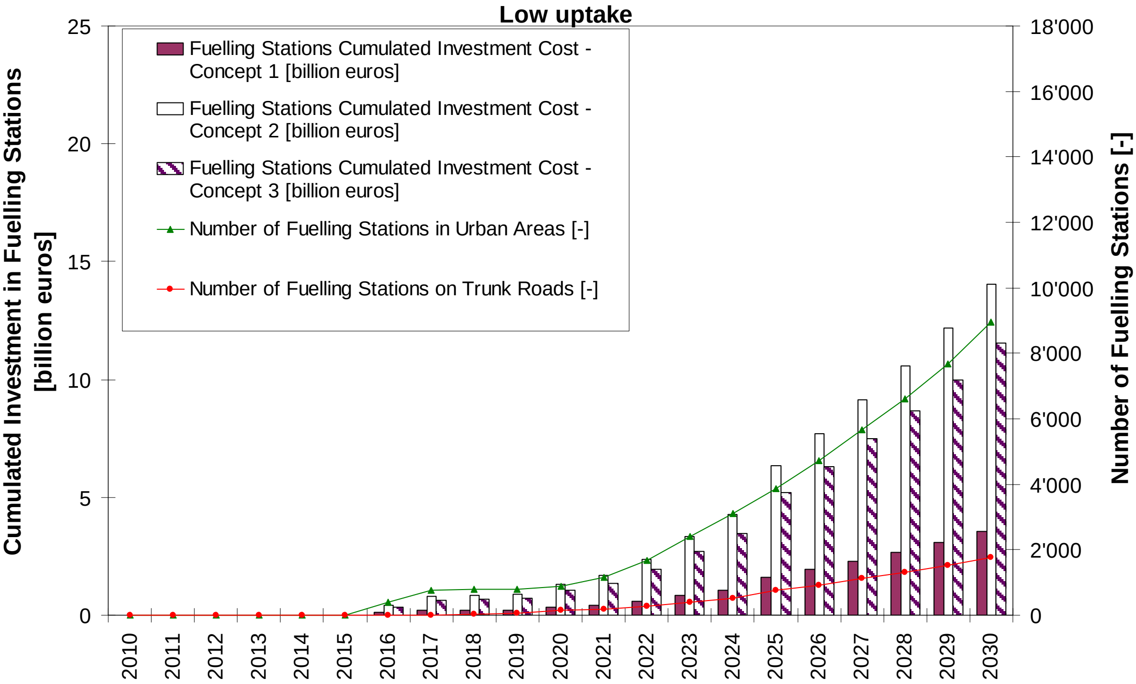


Figure 21: Number of fuelling stations and associated investment cost for low uptake and different fuelling concepts, scenario 1

4.4 Fuelling stations by country

Under the scenarios discussed, different countries begin to build fuelling stations at different times. This allows the vehicle manufacturers to roll out vehicles in consecutive regions rather than over a very wide area where they may not be easy to support and fuel. Figure 22 and Figure 23 below show the build-up of fuelling station infrastructure in different countries for the high and low penetration cases. As can be seen, in the high penetration case the number of fuelling stations in Germany reaches 5,000 by 2030, with 3,400 in the UK, 2,700 in France and just over 2,000 in Italy.

Figure 24 shows the number of fuelling stations by city in 2030, while Figure 25 to Figure 28 indicate fuelling station build-up and corresponding investment for selected cities. Different levels of urbanisation can be seen from the fact that in 2030, for the main countries, 22% of the hydrogen fuelling stations in France are on trunk roads, 18% in Germany and 15% in the United Kingdom, while Italy and Spain have 10%.

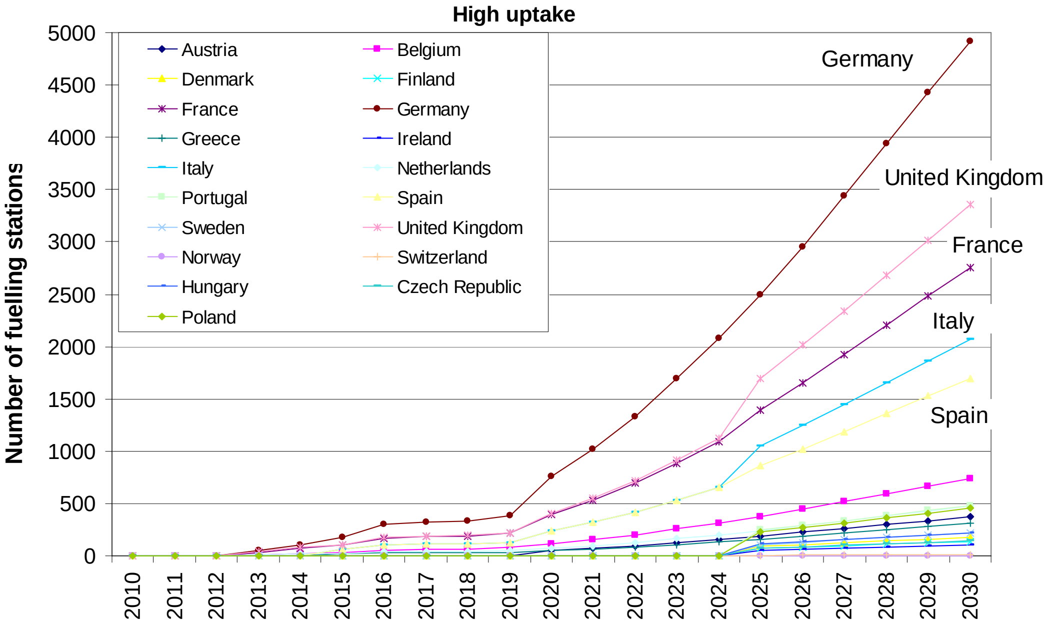


Figure 22: Fuelling stations by country, high uptake case, scenario 1

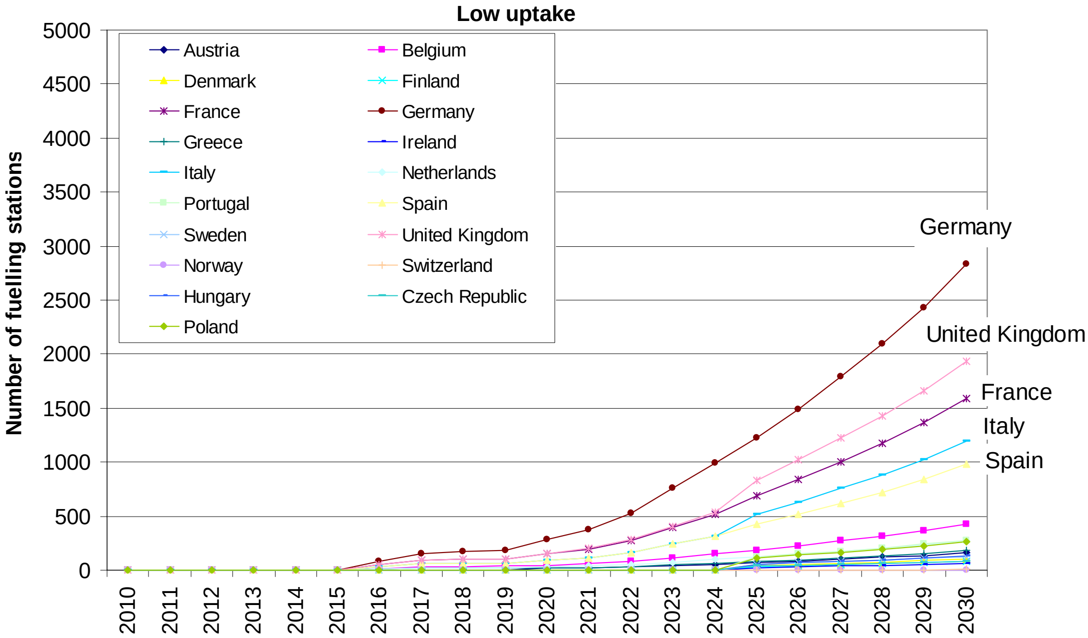


Figure 23: Fuelling stations by country, low uptake case, scenario 1

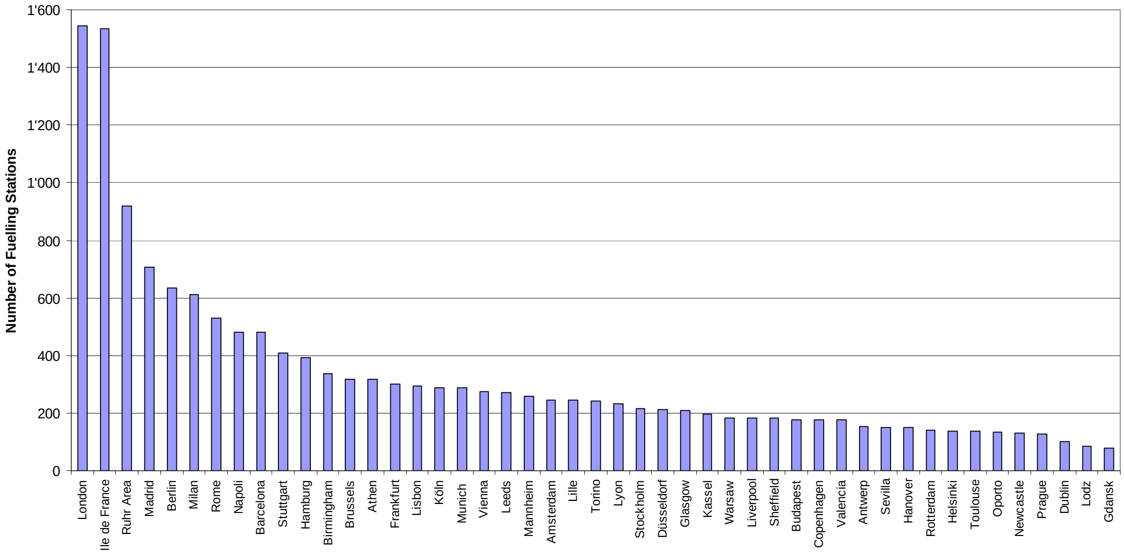


Figure 24: Fuelling stations by city, high uptake case, scenario 1

Figure 24 to Figure 28 illustrate that the form of development of infrastructure is the same within the major cities, as is to be expected given the methodology. It is also clear that investment in the fuelling stations by city is quite low in the early period, with investments in Berlin, for example, totalling less than 50m Euro for approximately 100 fuelling stations over the period to 2020. After this period, as cumulative costs begin to rise, the industry has considerably greater resources to draw upon for the investment in further stations, along with much lower risks of technology failure. The plateau in fuelling station build that is common to each city around 2016-2019 is due to the initial oversupply of stations to provide consumer comfort.

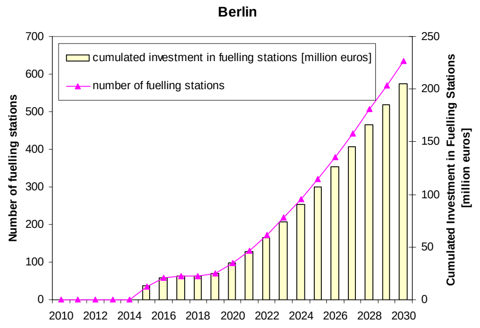


Figure 25: Number of fuelling stations and corresponding investment, scenario 1, high uptake, Berlin

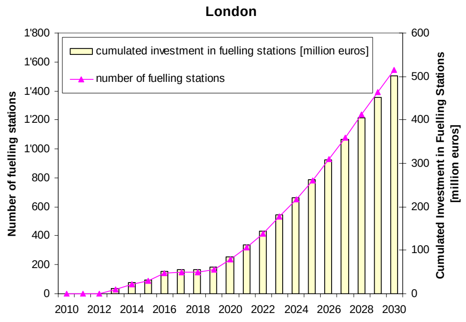


Figure 26: Number of fuelling stations and corresponding investment, scenario 1, high uptake, London

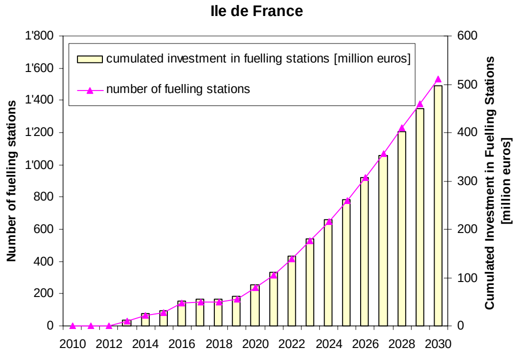


Figure 27: Number of fuelling stations and corresponding investment, high uptake, scenario 1, Île de France

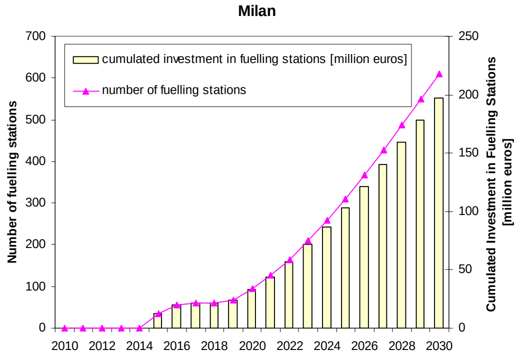


Figure 28: Number of fuelling stations and corresponding investment, high uptake, scenario 1, Milan

4.5 Costs by country

Figure 29 to Figure 32 show the total cumulative costs for the different countries considered, for 2020 and 2030, under Concept 1. The proportion of investment in each country is also shown. In these examples, German and the UK are always the largest contributors, due to the use of urban populations as a demand indicator. BY 2030, under the high uptake case, they spend 5bn Euros and 4bn Euros respectively.

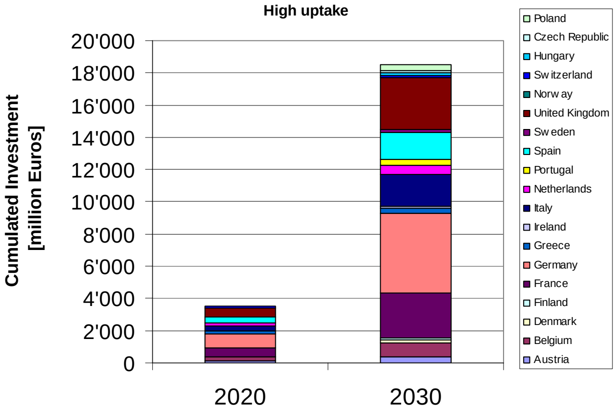


Figure 29: Total cumulative investment by country, high uptake, concept 1, scenario 1

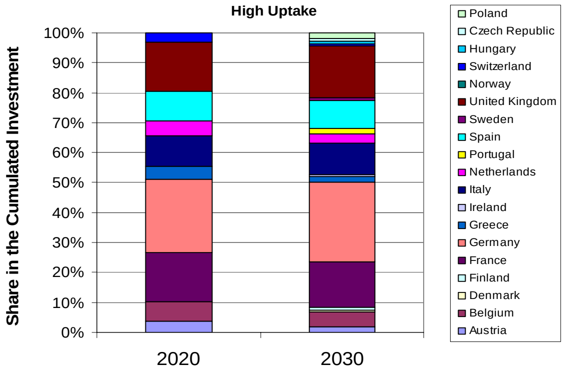


Figure 30: Proportion of cumulative investment by country, high uptake, concept 1, scenario 1

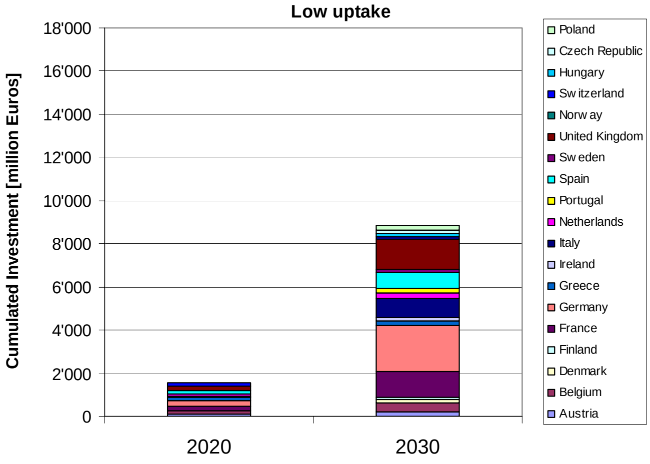


Figure 31: Total cumulative investment by country, low uptake, concept 1, scenario 1

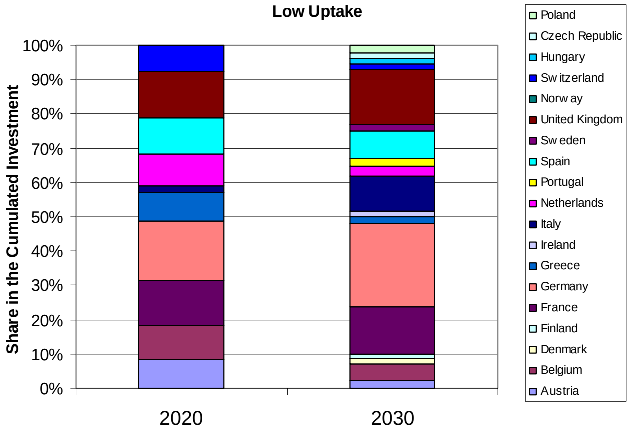


Figure 32: Proportion of cumulative investment by country, low uptake, concept 1, scenario 1

4.6 Decomposition by actor and country

The different infrastructure concepts have very different characteristics in terms of investment, and hence for the different actors under consideration. In Concept 1, the centralised option in which liquid hydrogen is delivered by tanker, production plant costs appear highest. This is because the other concepts include some of the production costs – those on-site – as part of the fuelling station costs. However, the centralised concept also benefits most from economies of scale – the total investment costs are lowest of the three by a considerable margin.

Of the 18.5bn Euro invested from 2010-2030 under the high uptake scenario in Concept 1 (Figure 33), about one-third can be regarded as ‘pure’ fuelling infrastructure – fuelling station equipment. Financing this is a different issue from the other cases under consideration, where more equipment is local to the fuelling site. Different actors are required. Figure 34 shows the low uptake scenario results.

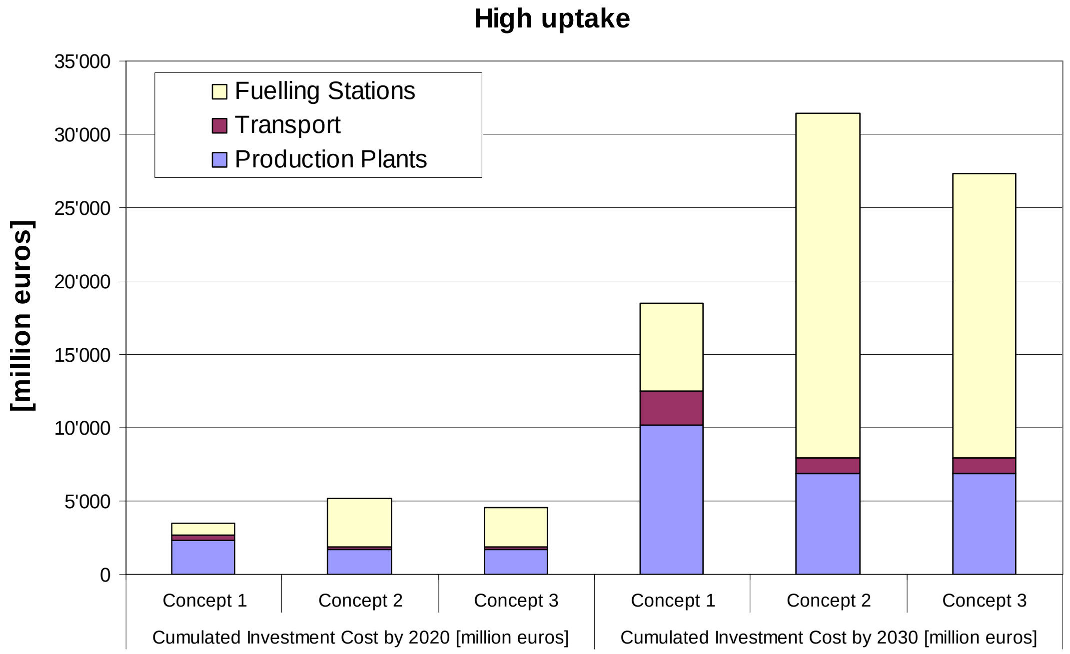


Figure 33: Total investment cost split by production, distribution and transport; high uptake, scenario 1

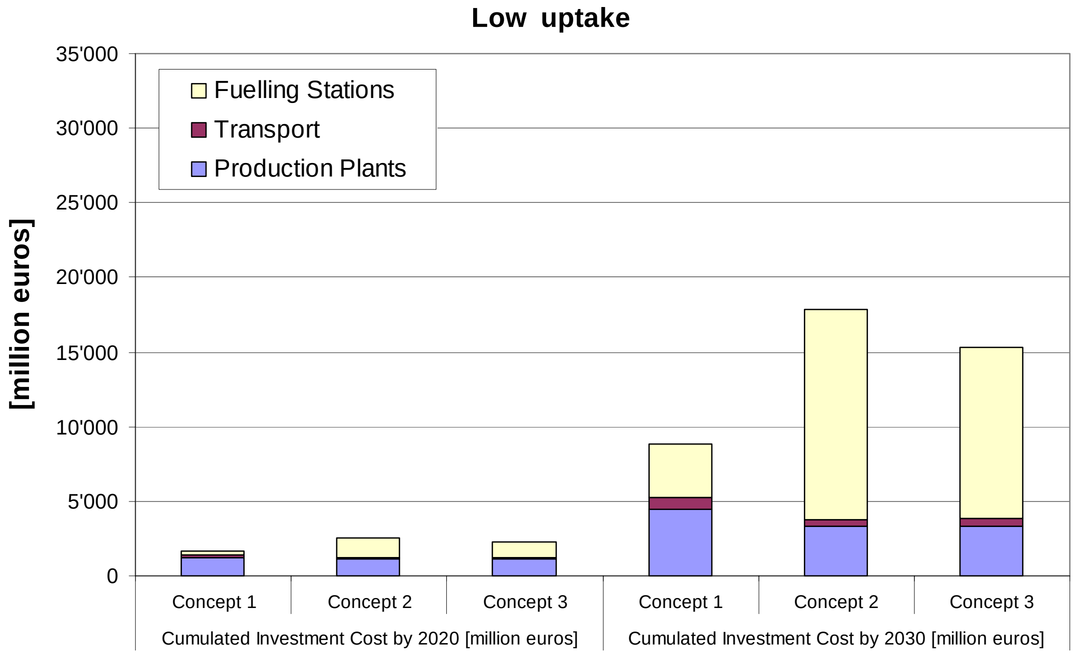


Figure 34: Total investment cost split by production, distribution and transport; low uptake, scenario 1

Figure 35 shows the annual investment in infrastructure across Europe for Concept 1, which varies between 100m Euros early on and 2.5bn Euros in 2025. The four infrastructure stages can be clearly seen in the higher step investment figures at approximately five year intervals. The first of these (2016) is delayed by a year, due to the availability up to that point of sufficient ‘excess’ industrial hydrogen to fuel the existing vehicles.

Concepts 2 and 3 are shown in Figure 36 and Figure 37, respectively. Similar lumpy investment is shown, exaggerated by the additional costs associated with on-site systems.

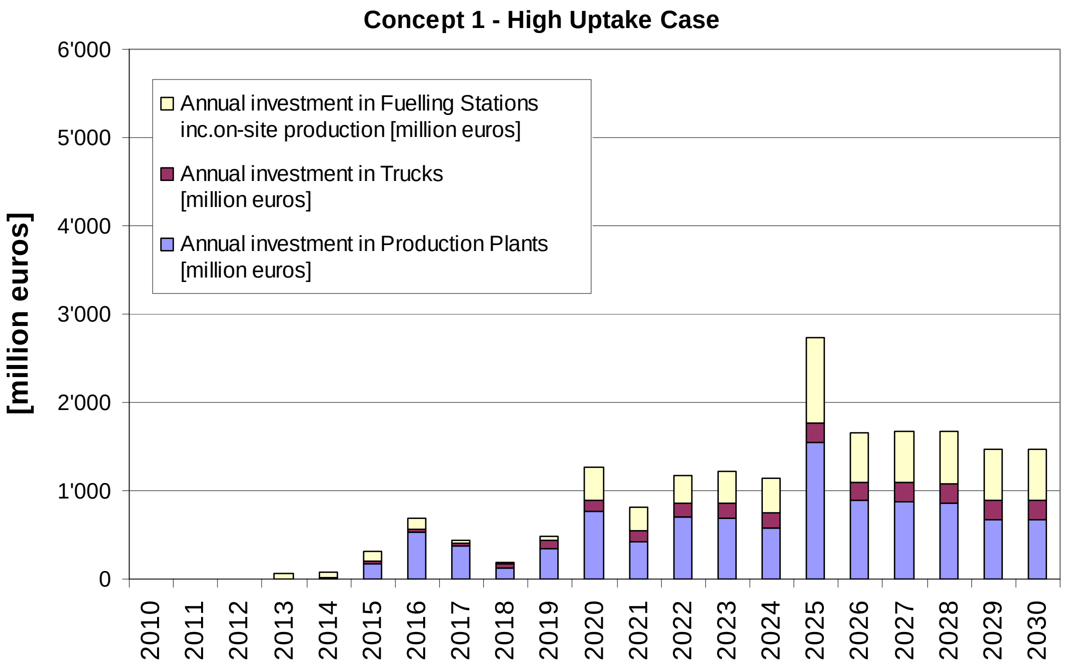


Figure 35: Annual investment cost in Europe split by production, distribution and transport; high uptake, Concept 1, scenario 1

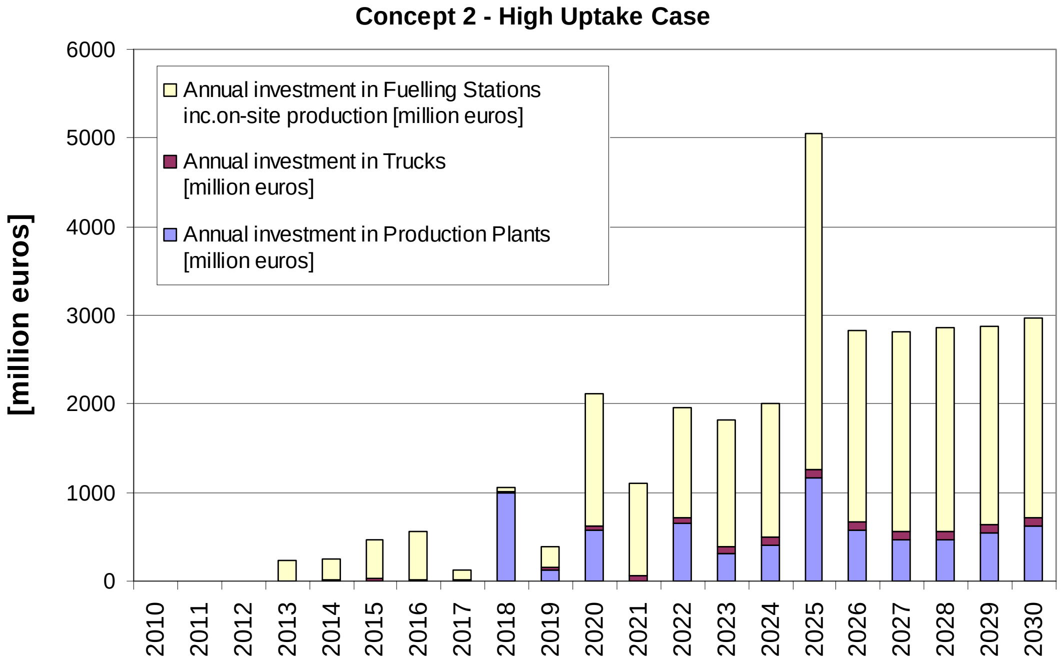


Figure 36: Annual investment cost in Europe split by production, distribution and transport; high uptake, Concept 2, scenario 1

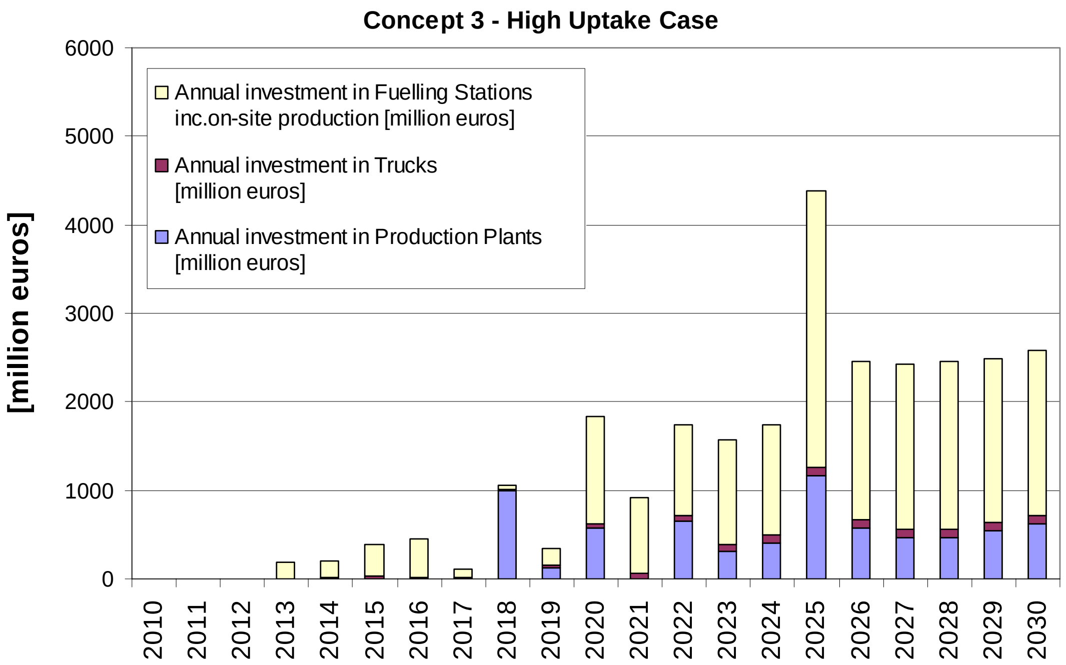


Figure 37: Annual investment cost in Europe split by production, distribution and transport; high uptake, Concept 3, scenario 1

The cumulative investments shown for the high uptake case in Europe in Figure 38 to Figure 40 show the significant differences between concept 1 – the centralised production infrastructure – and the two on-site methods. Each of the 'on-site' cases suffers from the less favourable costs, and economies of scale, of the smaller technologies.

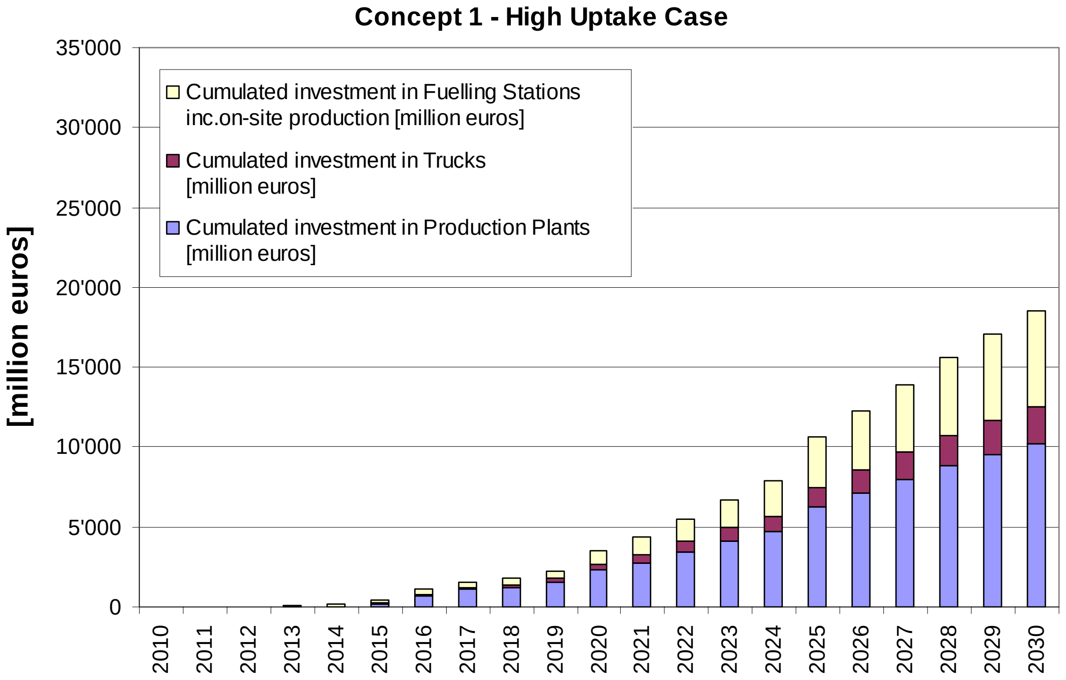


Figure 38: Cumulative annual investment cost in Europe split by production, distribution and transport; high uptake, Concept 1, scenario 1

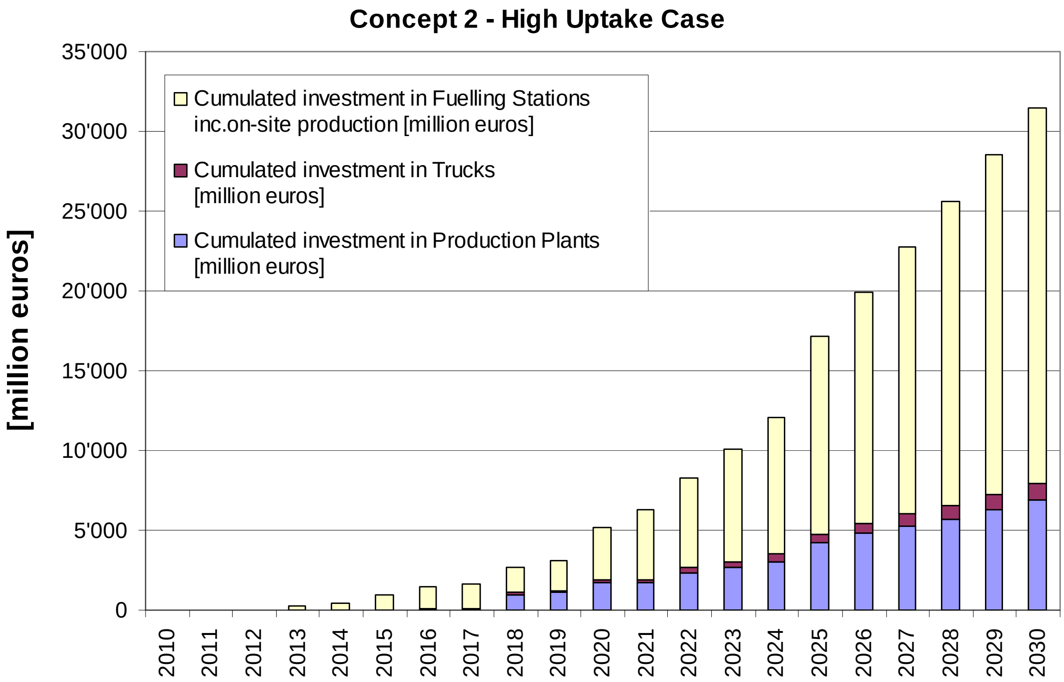


Figure 39: Cumulative annual investment cost in Europe split by production, distribution and transport; high uptake, Concept 2, scenario 1

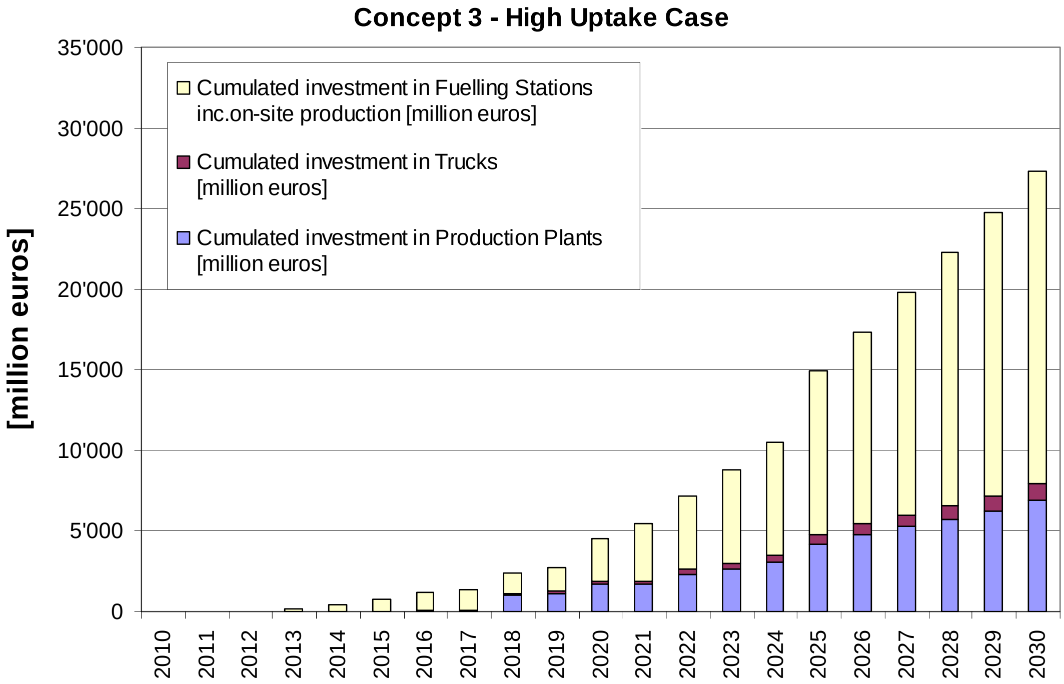


Figure 40: Cumulative annual investment cost in Europe split by production, distribution and transport; high uptake, Concept 3, scenario 1

4.7 Investment results

In order to illustrate how different actors might participate in the development of an infrastructure, and what implications it might have, we have split the investment in different infrastructure components in different ways. In the majority of the countries investigated, many companies provide fuelling stations. Of these, typically four or five are major corporations with the financial muscle to be able to undertake risky investments. To be conservative, we have assumed that actually three different companies choose to participate equally in fuelling station provision.

For production and transport, the picture is typically more consolidated. However, in most cases at least two different major companies could provide hydrogen to filling stations in each country. We have therefore assumed that two companies assume equal responsibility for this in each country.

The selection of figures below indicate the costs and revenues for any one of those single actors in the chain – one of the two producers, or one of the three distributors. The total costs and revenues for the country may therefore be found by multiplying up the individual numbers by the number of actors. This analysis indicates both the level of investment that might be required for a single actor in a country (and of course some of these actors will be required to invest in more than one country), and also the possible revenues accruing from the sale of hydrogen.

As stated in the introduction, two key modelling assumptions have been made. The first is that the hydrogen is not taxed, so the price to the consumer – competitive with taxed gasoline – is pure revenue to the industry. However, the gasoline price is also assumed to remain constant throughout the period, which is very unlikely given past trends, and will counteract the absence of tax to some extent. The second assumption is that the producer will always sell hydrogen to the distributor at 80% of the final consumer price, resulting in a fixed ratio of revenues.

These assumptions are not completely realistic. However, in the interim period while hydrogen demand is very low in comparison to conventional fuels, and tax revenue is therefore small, it is not unreasonable to assume that governments might choose not to impose a duty. In the longer term they will wish to, if only to ensure tax revenues are maintained. Equally, the selling price and profit margin will be decided by local market forces, and the proportions of revenue will therefore change accordingly. The distributors with on-site production will also control more of their revenue streams.

Figure 41 to Figure 46 show, side by side, the costs and revenues for the producers and the distributors of hydrogen in Germany over the period to 2030. By inspection it can be seen that the picture appears slightly more attractive for the producers, as is the case with fuel provision today. Energy industry figures suggest that profit is primarily generated on exploration and production, rather than in final fuel sales.

The three sets of charts show the three concepts under investigation – one with only centralised production of hydrogen, and two concepts with a proportion of on-site production. The electrolysis concept (concept 3) suffers by comparison with the others. This is due to the high cost of electricity in comparison with natural gas, which makes the production of hydrogen considerably more expensive, while a fixed hydrogen price to the consumer is assumed.

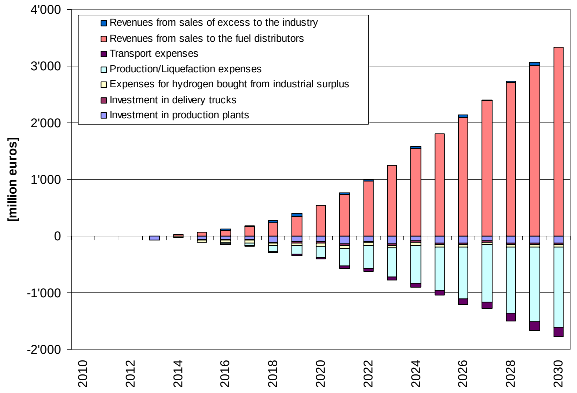


Figure 41: Annual undiscounted costs and revenues for one of two producer/transporters in Germany for concept 1, high uptake, scenario 1

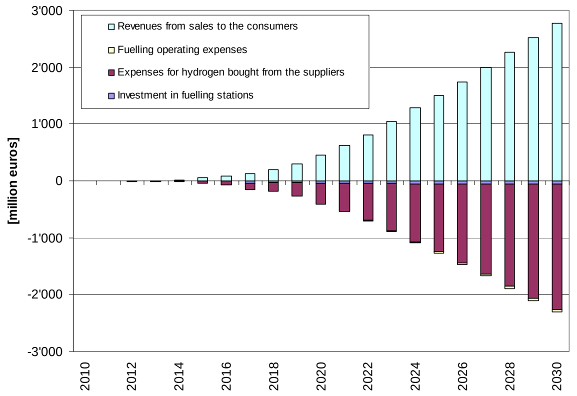


Figure 42: Annual undiscounted costs and revenues for one of three distributors in Germany for concept 1, high uptake, scenario 1

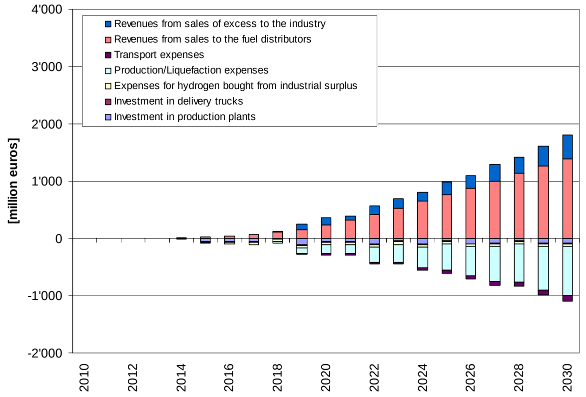


Figure 43: Annual undiscounted costs and revenues for one of two producer/transporters in Germany for concept 2, high uptake, scenario 1

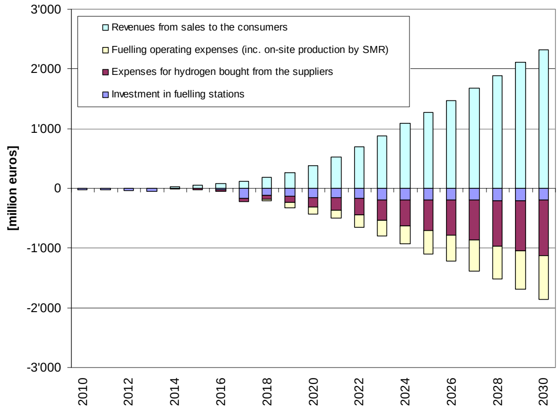


Figure 44: Annual undiscounted costs and revenues for one of three distributors in Germany for concept 2, high uptake, scenario 1

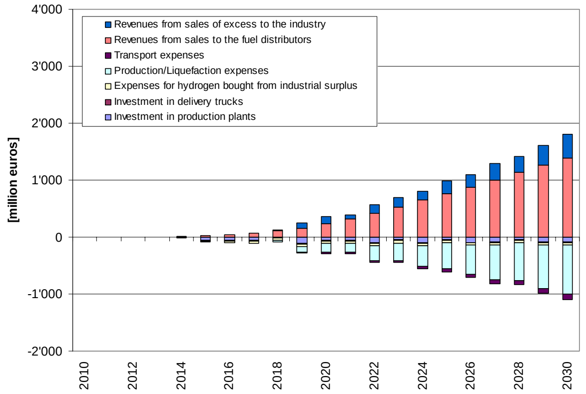


Figure 45: Annual undiscounted costs and revenues for one of two producer/transporters in Germany for concept 3, high uptake, scenario 1

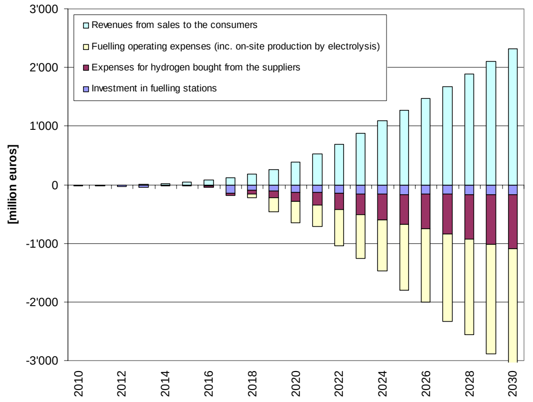


Figure 46: Annual undiscounted costs and revenues for one of three distributors in Germany for concept 3, high uptake, scenario 1

Figure 47 to Figure 52 show discounted cumulated cashflow results for several of the larger countries in Europe, indicating break-even points for producers and distributors under the different concepts. Under the model conditions, the picture for producers changes only marginally, with break-even around 2020 in the different countries. The slightly different timing is due to the different hydrogen prices within those countries, and the costs of production. The UK is quite favourable for producers, as current data show high gasoline prices for the consumer and low natural gas and electricity prices at the same time. Nevertheless, the higher uptake in Germany means that it is more profitable in the long term.

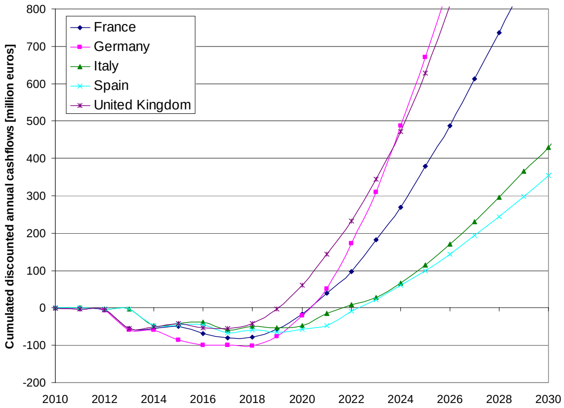


Figure 47: Break-even for one of two producers/transporters in selected EU countries, concept 1, high uptake, scenario 1

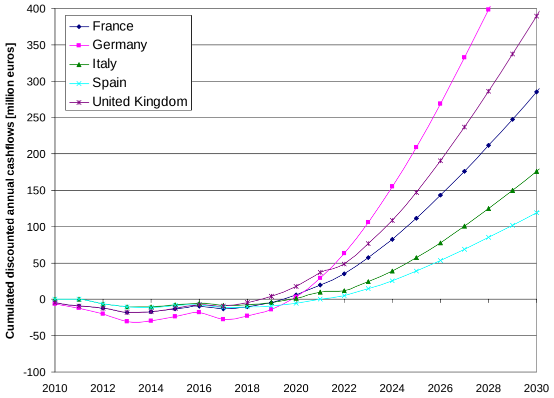


Figure 48: Break-even for one of three distributors in selected EU countries, concept 1, high uptake, scenario 1

Figure 48 shows that under the centralised production case the distributor also has a comparatively early break-even, though clearly a period of around ten years before cashflows become positive suggests that larger companies will be at an advantage. The picture is more difficult for the distributors also producing their own hydrogen on-site, as production costs are higher but final hydrogen price remains the same. In this global simplified picture it looks as though on-site production from steam reformers can be profitable, but that electrolytic production on-site is less positive. In reality this will depend on local pricing structures, and decentralised electrolysis must be considered with a clear understanding of local conditions.

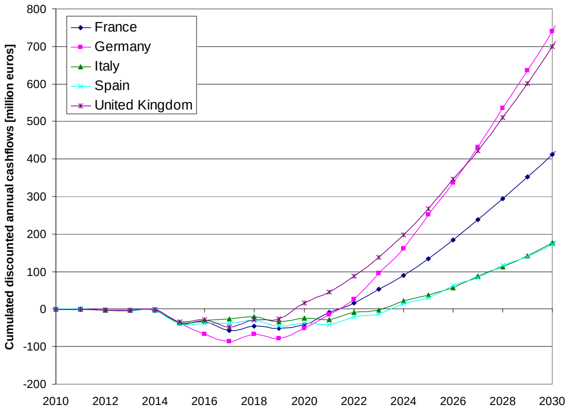


Figure 49: Break-even for one of two producers/transporters in selected EU countries, concept 2, high uptake, scenario 1

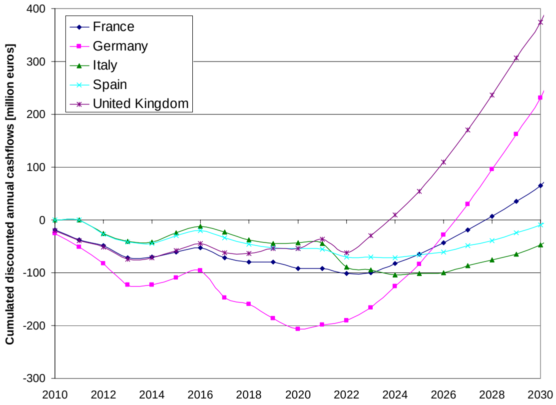


Figure 50: Break-even for one of three distributors in selected EU countries, concept 2, high uptake, scenario 1

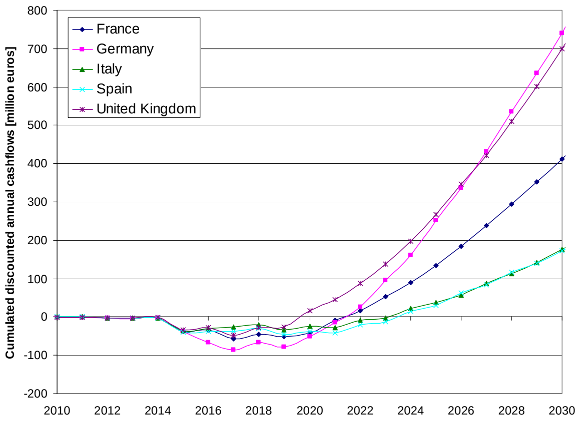


Figure 51: Break-even for one of two producers/transporters in selected EU countries, concept 3, high uptake, scenario 1

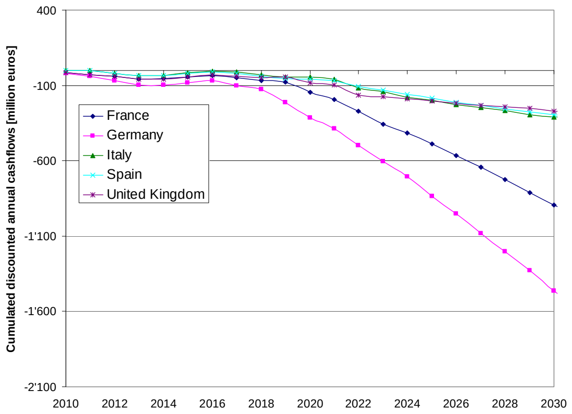


Figure 52: Break-even for one of three distributors in selected EU countries, concept 3, high uptake, scenario 1

The final set of charts, Figure 53 to Figure 55, show the overall cashflow picture for Europe, firstly for a consolidated global producer and distributor – responsible for all hydrogen production and distribution respectively – and then for one that manages the entire fuel chain. The three concepts are shown as before. The producer is shown to break even around 2020, with slightly longer required if some on-site production is considered, while the distributor only breaks even within the same timeframe for concept 1. Under concept 2, the cashflow becomes positive after a longer period, but once again electrolysis is too expensive under the model assumptions shown here.

The integrated producer/distributor can be seen to have cashflow in line with the previous disaggregated analysis, with concept 1 becoming positive in 2020, concept 2 in 2027, and concept 3 not showing a profit within the modelling horizon of the analysis. This aggregation of results is helpful in a European context, but must be considered on a more sophisticated level by any single corporation.

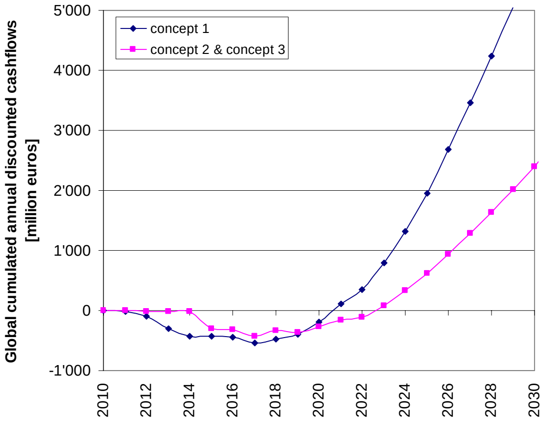


Figure 53: Break-even for one single producer/transporter in Europe, concept 1, 2 and 3, high uptake, scenario 1

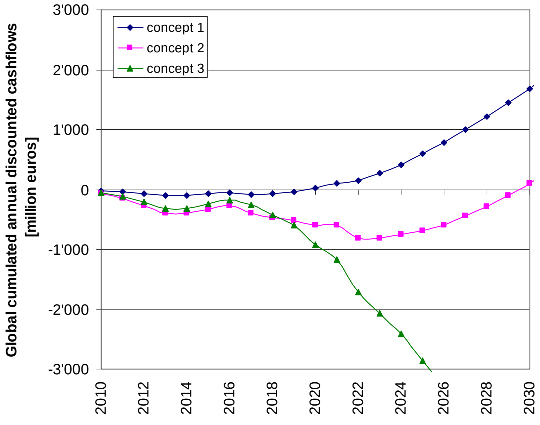


Figure 54: Break-even for one single distributor in Europe, concept 1, 2 and 3, high uptake, scenario 1

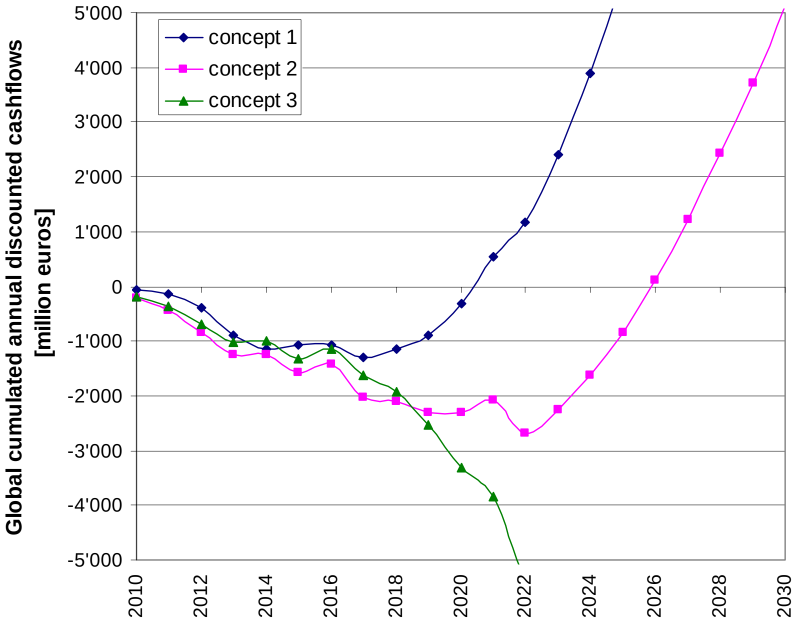


Figure 55: Break-even for one integrated supplier in Europe, concept 1, 2 and 3, high uptake, scenario 1

4.8 Scenario 2

In scenario 2, the same overall vehicle penetration is considered, but with a different geographical distribution. Vehicle uptake is more concentrated, initially into Germany, and gradually into neighbouring countries. This scenario would represent a strong lead by an individual country. The underlying assumptions for the development are the same, in terms of fuelling station costs, fuel prices, and the number of vehicles produced. However, the more concentrated nature of the development changes investment parameters, and hence the time required for positive cashflow.

As shown in Figure 56, under the high penetration case in scenario 2 (which runs only to 2025) some 20m hydrogen vehicles are on the road by the end of the period, with corresponding hydrogen demand of 3.5 Mt. In the low uptake case (Figure 57) the corresponding figures are 6m vehicles and 1Mt hydrogen. Figure 58 shows the breakdown between urban and trunk road-related demand over both penetration rates.

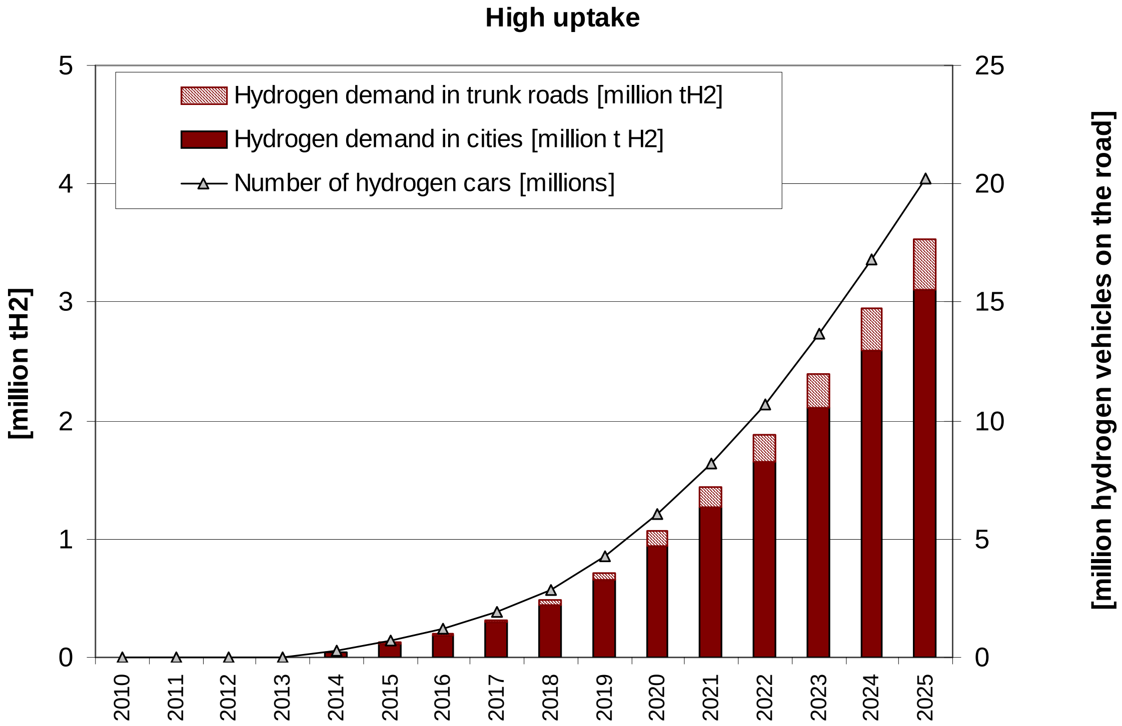


Figure 56: Hydrogen vehicle uptake and corresponding hydrogen demand to 2025, high uptake case, scenario 2

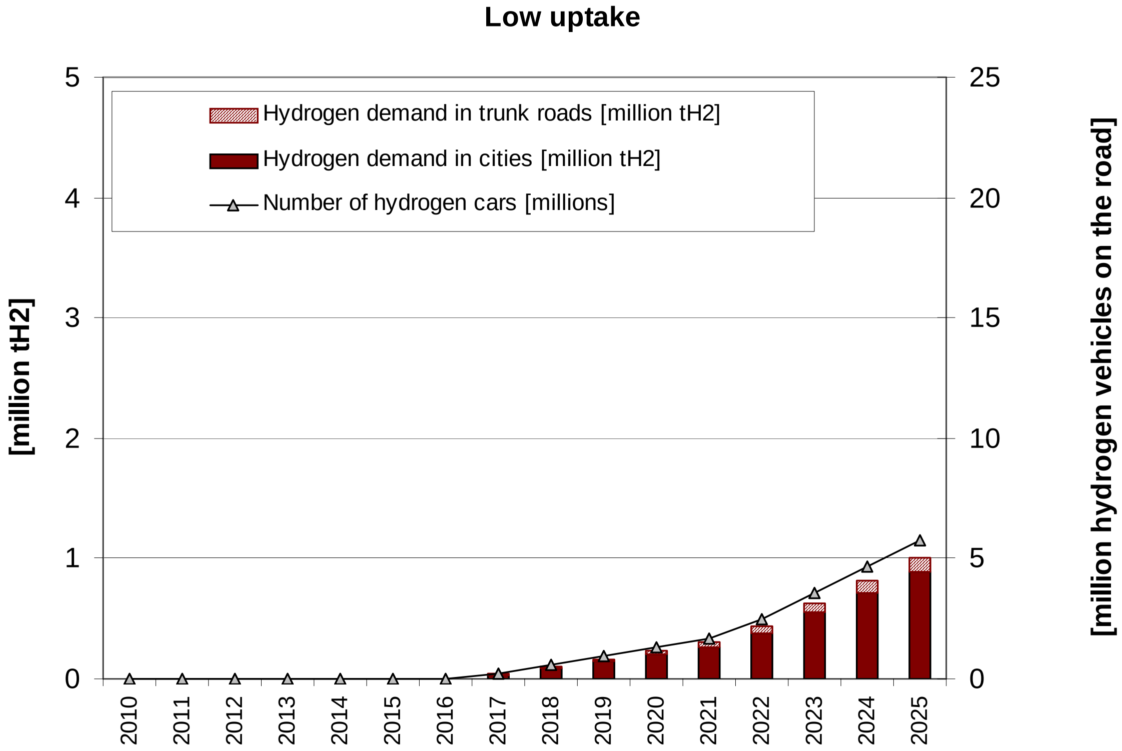


Figure 57: Hydrogen vehicle uptake and corresponding hydrogen demand to 2025, low uptake case, scenario 2

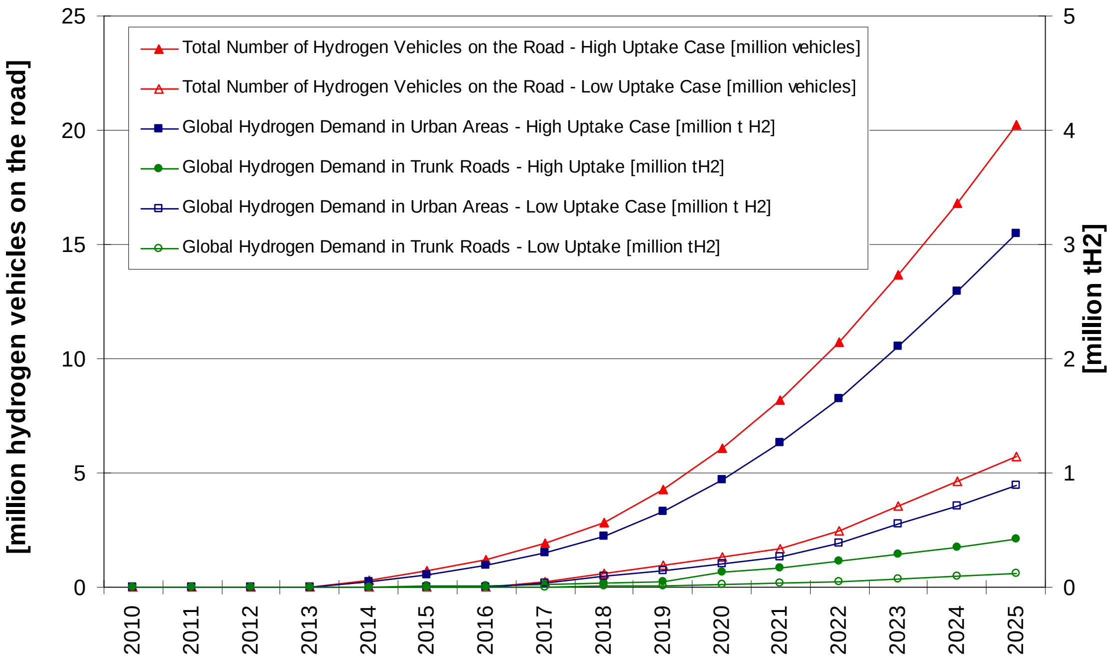


Figure 58: Hydrogen demand for urban and trunk road fuelling stations to 2025, scenario 2, high and low uptake

4.9 Vehicle penetration by country

Figure 59 and Figure 60 demonstrate the uptake of vehicles in the different countries considered. Once again, Germany dominates, due to its position early in the development of the infrastructure. By 2025 over 6m vehicles are on the road in the high penetration case, while in the low case the figure is approaching 2m. Corresponding figures for the high uptake case for France are 4.5m vehicles, and for the UK 3m.

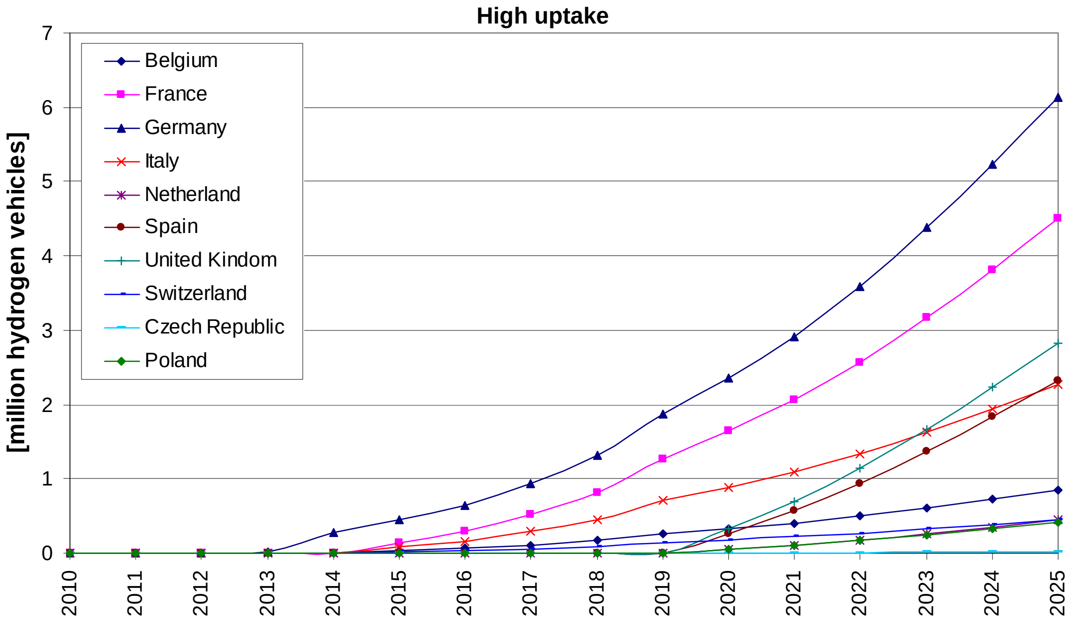


Figure 59: Hydrogen vehicle uptake by country, high penetration case, scenario 2

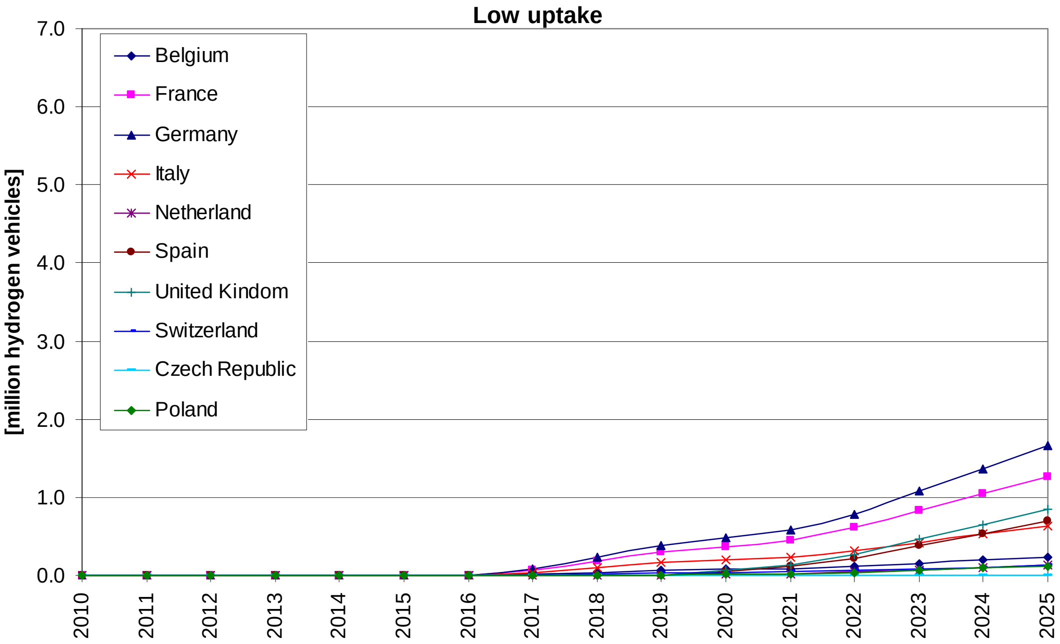


Figure 60: Hydrogen vehicle uptake by country, low penetration case, scenario 2

Once again the model allows for very high levels of initial penetration of fuelling stations – 30 times more than would be required in the first year – to allow customers a sense of security that fuel will be available. Figure 61 shows the resulting gap between installed capacity and demand while vehicle numbers catch up with fuel availability. This is assumed to take about 7 years.

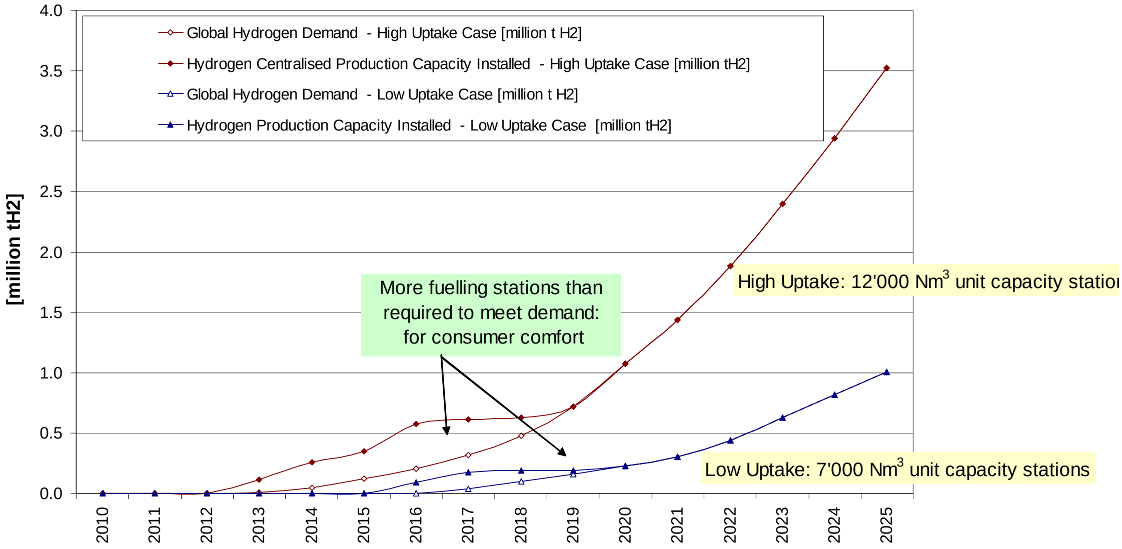


Figure 61: Hydrogen demand and installed production capacity in early period of uptake, scenario 2

4.10 Fuelling stations by country

As can be seen in Figure 62, for the high penetration case in scenario 2, nearly 8,000 fuelling stations providing hydrogen are required in urban areas in 2025, and 1,000 on trunk roads. Cumulative investment for case 1 is around 3bn Euros over that period, and 9-12bn Euros for the distributed cases. Figure 63 gives the same data for the low penetration scenario, where half of the number of fuelling stations is in place.

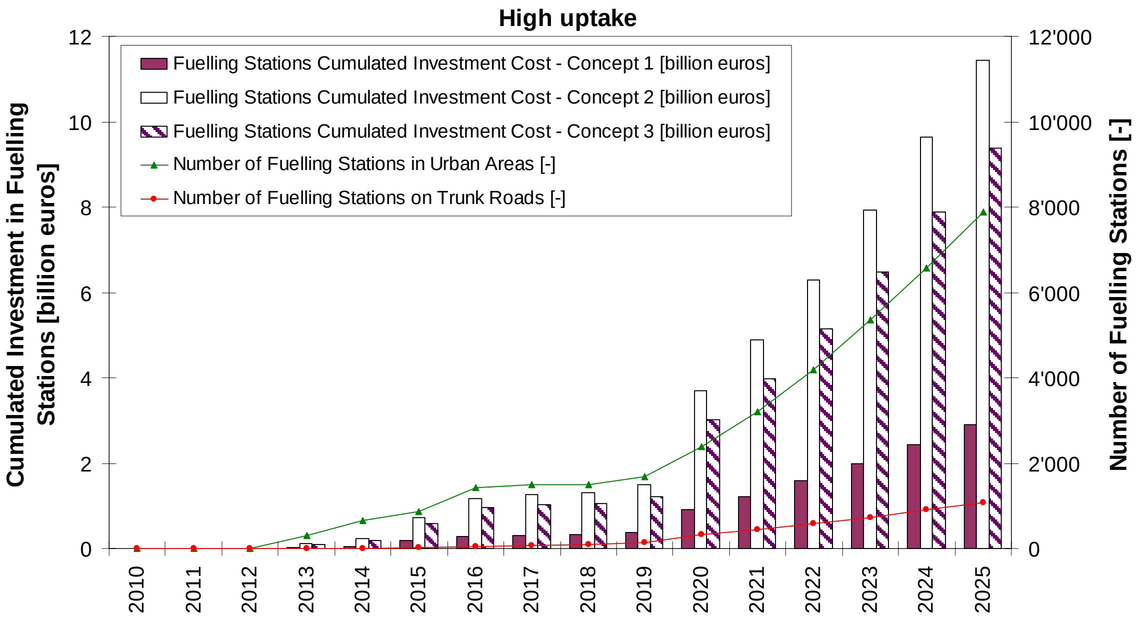


Figure 62: Number of fuelling stations and associated investment cost for high uptake and different fuelling concepts, scenario 2

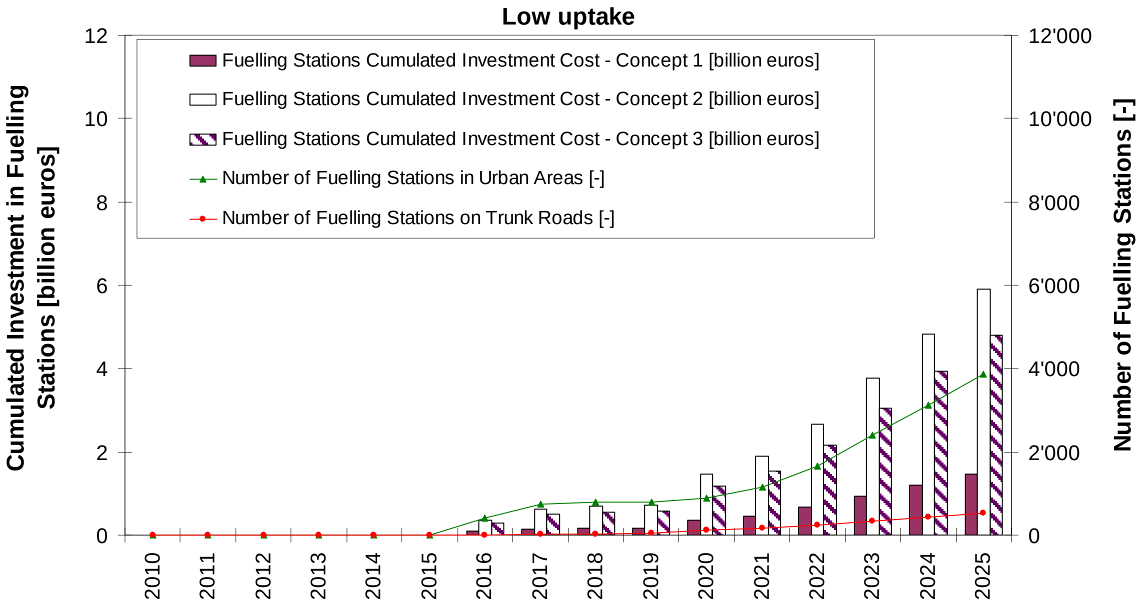


Figure 63: Number of fuelling stations and associated investment cost for low uptake and different fuelling concepts, scenario 2

4.11 Fuelling stations by country

Figure 64 and Figure 65 show the number of fuelling stations in selected countries over the period to 2025, when 2,500 have been built in Germany under the high uptake case, nearly 2,000 in France, and 1,500 in the UK.

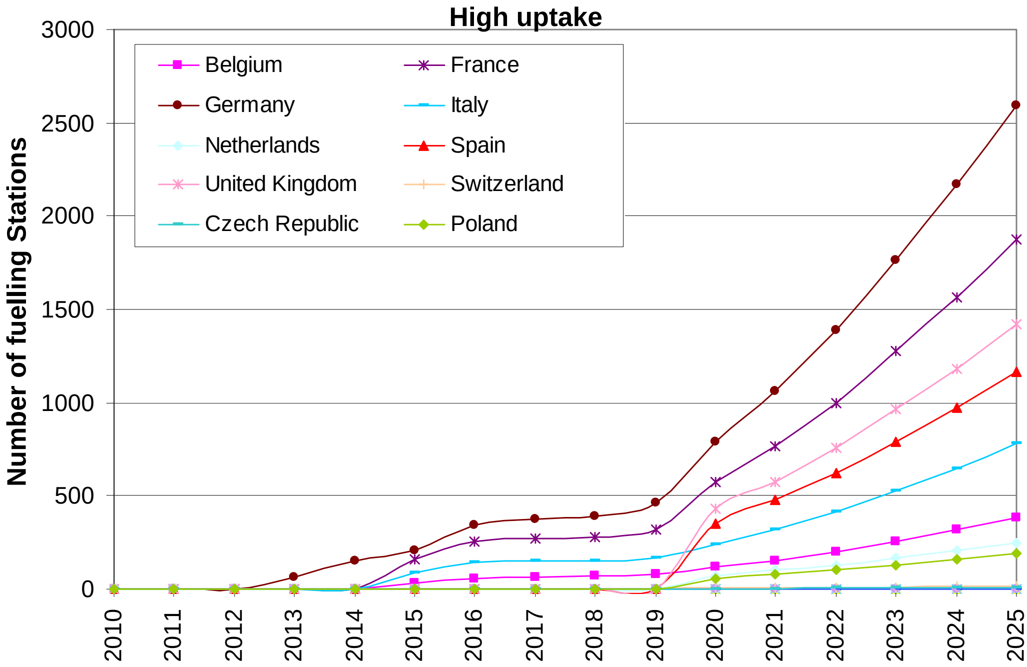


Figure 64: Fuelling stations by country, high uptake case, scenario 2

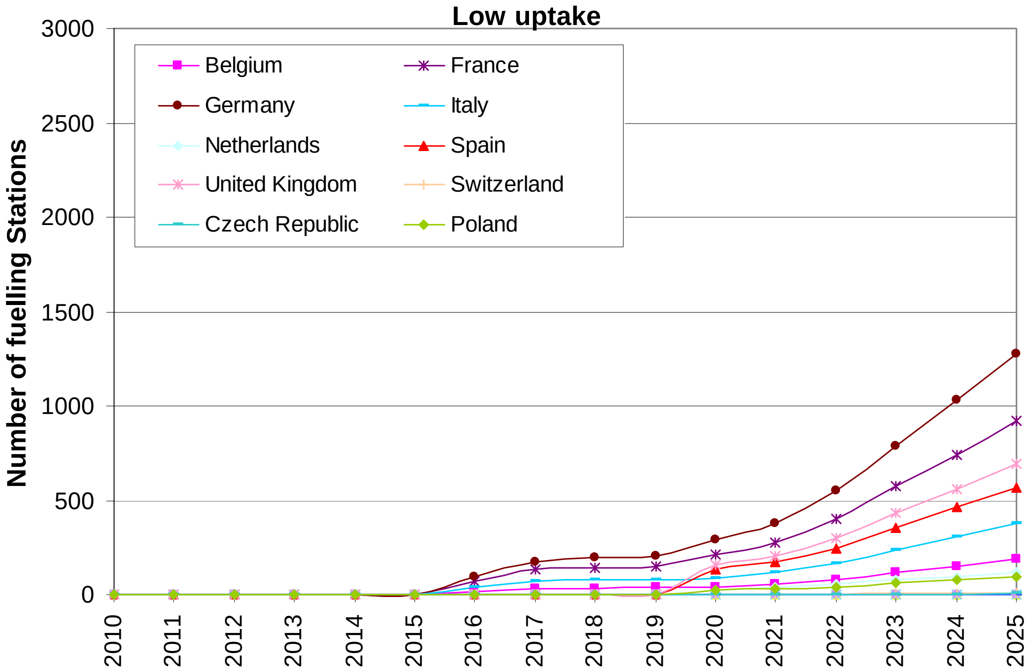


Figure 65: Fuelling stations by country, low uptake case, scenario 2

4.12 Costs by country

Figure 66 to Figure 69 show the total cumulative costs for the different countries considered under scenario 2, for 2015 and 2025, under Concept 1. The proportion of investment in each country is also shown. In this case, the Czech Republic emerges as a major stakeholder in the 2015 timeframe, with 30% of the investment (in a low total). The proportion is much lower by 2025 as other countries have higher uptake rates for hydrogen vehicles.

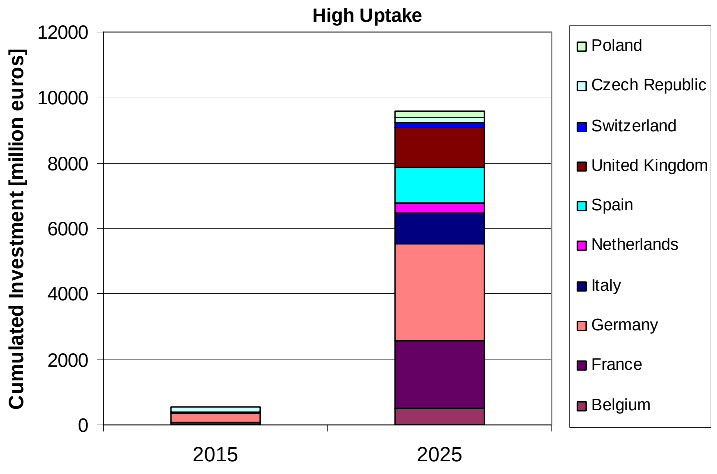


Figure 66: Total cumulative investment by country, high uptake, concept 1, scenario 2

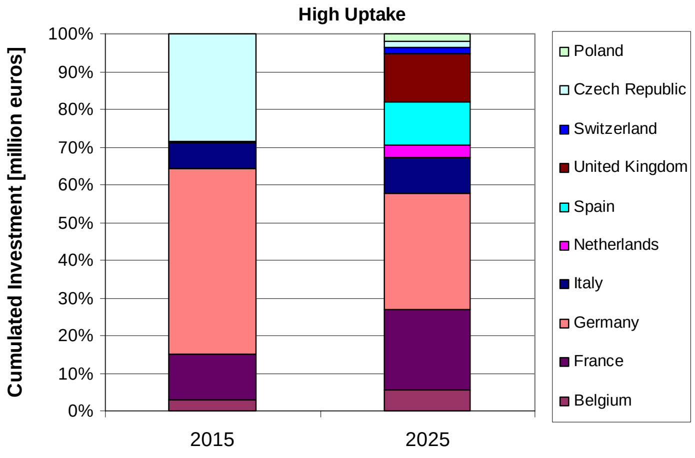


Figure 67: Proportion of cumulative investment by country, high uptake, concept 1, scenario 2

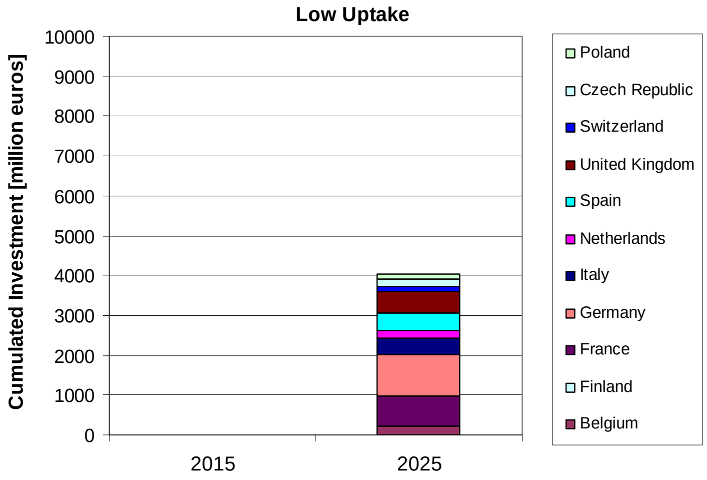


Figure 68: Total cumulative investment by country, low uptake, concept 1, scenario 2

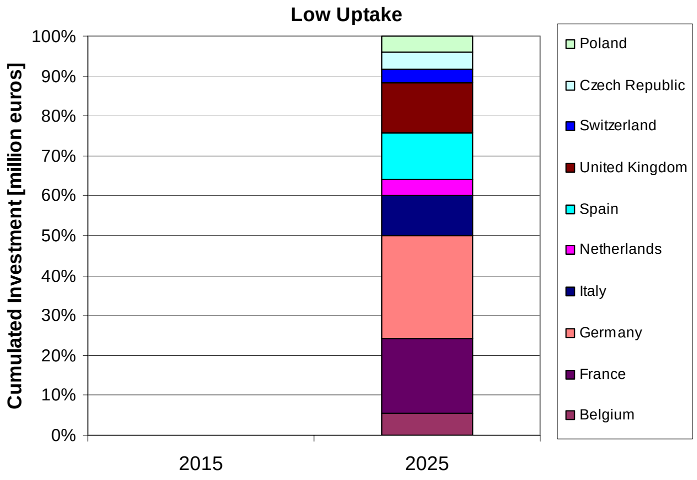


Figure 69: Proportion of cumulative investment by country, low uptake, concept 1, scenario 2

4.13 Decomposition by actor and country

One of the key differences between scenarios 1 and 2 is the more limited initial range of countries involved in the latter. This has an impact on investment costs and on flows of cost and revenue. As in scenario 1, the three concepts (centralised, centralised plus on-site SMR, and centralised plus on-site electrolysis) are increasingly expensive. This is again due to the choice of parameters for the model.

Under this scenario, about 10bn Euros of investment are required for concept 1 in the high uptake case. Nearly 6bn of this is devoted to production plant, while 1bn is put towards delivery tankers and the remainder invested in fuelling stations. Concepts 2 and 3 demonstrate lower production and transport costs – about 4bn Euros – but 9-10bn Euros in on-site fuelling station costs.

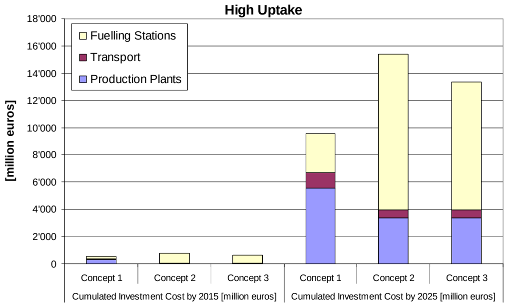


Figure 70: Total investment cost split by production, distribution and transport; high uptake, scenario 2

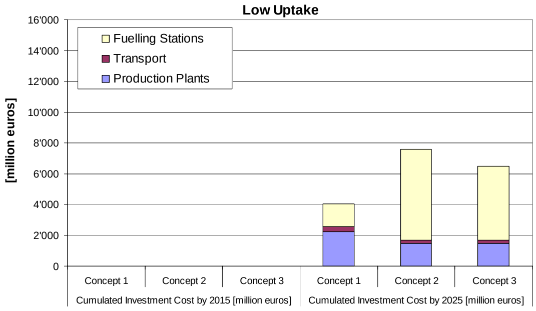


Figure 71: Total investment cost split by production, distribution and transport; low uptake, scenario 2

Annual investment for the high uptake case and for concepts 1 to 3 respectively is shown in Figure 72, Figure 74 and Figure 76, while Figure 73, Figure 75 and Figure 77 show cumulative investment.

Once again, investments are somewhat lumpy, driven by the development phases in the model. Maximum annual investment over the period to 2025 is just over 1.5bn Euros for concept 1 – in 2025; close to 3bn Euros for concept 2, but in 2020; and 2.5bn Euros for concept 3, also in 2020. Investment is also high in 2020 for concept 1, but the magnifying effect of the high costs of on-site systems mean that this of more importance for the decentralised concepts 2 and 3.

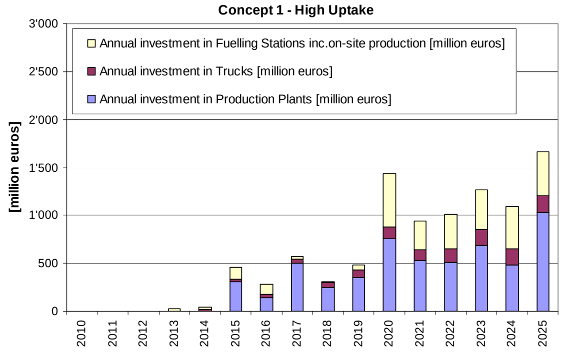


Figure 72: Annual investment cost in Europe split by production, distribution and transport; high uptake, concept 1, scenario 2

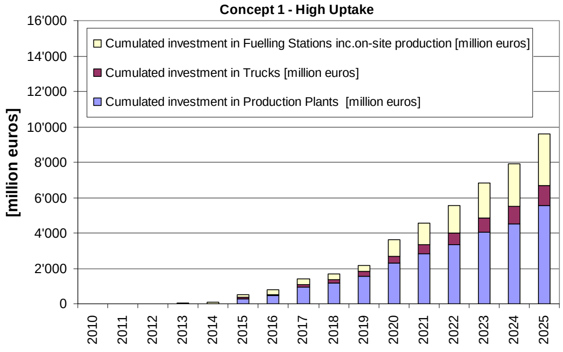


Figure 73: Cumulative annual investment cost in Europe split by production, distribution and transport; high uptake, concept 1, scenario 2

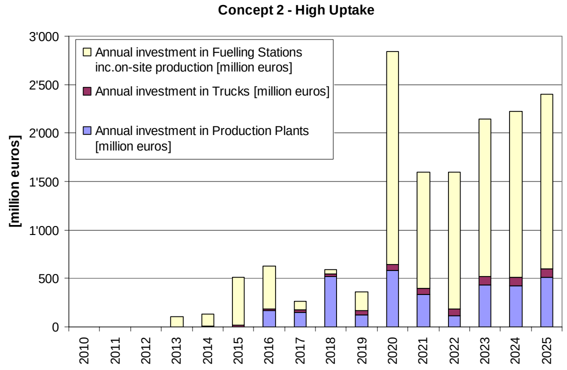


Figure 74: Annual investment cost in Europe split by production, distribution and transport; high uptake, concept 2, scenario 2

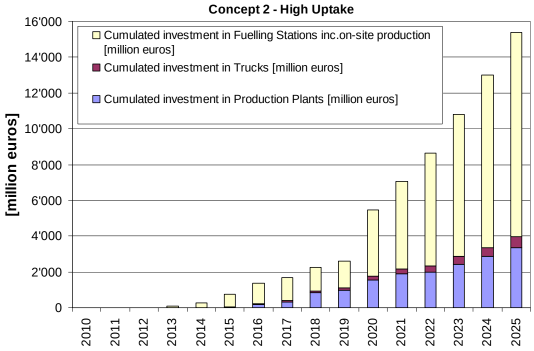


Figure 75: Cumulative annual investment cost in Europe split by production, distribution and transport; high uptake, concept 2, scenario 2

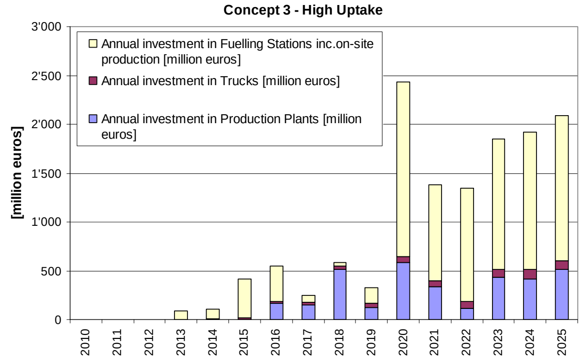


Figure 76: Annual investment cost in Europe split by production, distribution and transport; high uptake, concept 3, scenario 2

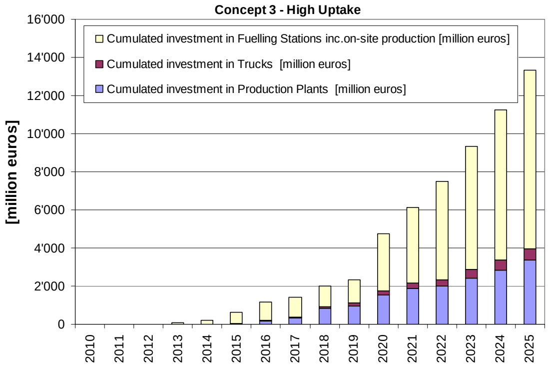


Figure 77: Cumulative annual investment cost in Europe split by production, distribution and transport; high uptake, concept 3, scenario 2

Figure 78 to Figure 83 show the individual and cumulative annual investment costs for a single country, Germany, over the period to 2025. Annual costs under concept 1 are highest in 2025 at over 450m Euro; over 700m Euro for concept 2, in 2024; and just under the same figure for concept 3. Cumulative costs rise to 3bn Euros for concept 1 and 4.5bn and 4bn Euros for 2 and 3, respectively.

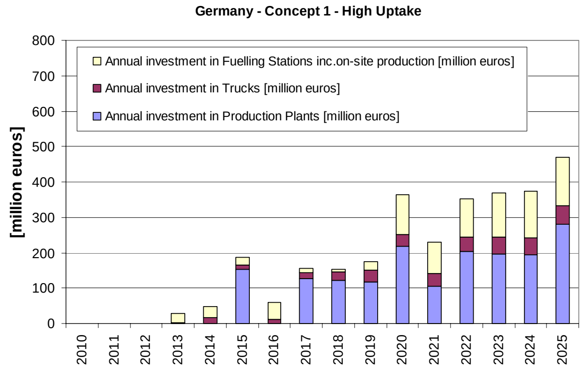


Figure 78: Annual investment cost in Germany split by production, distribution and transport; high uptake, concept 1, scenario 2

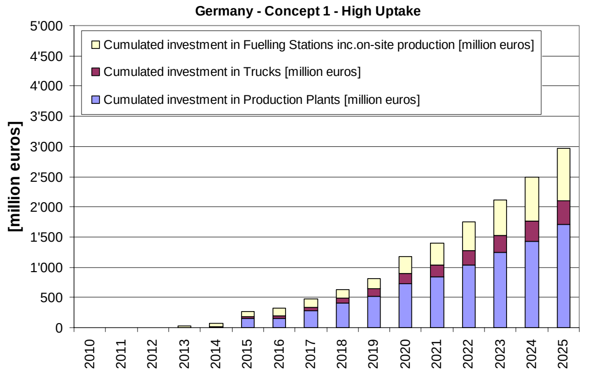


Figure 79: Cumulative annual investment cost in Germany split by production, distribution and transport; high uptake, concept 1, scenario 2

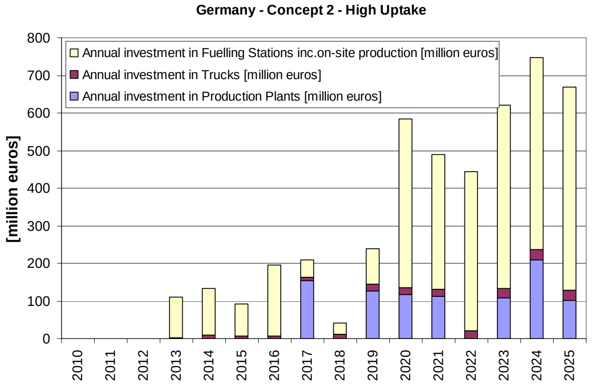


Figure 80: Annual investment cost in Germany split by production, distribution and transport; high uptake, concept 2, scenario 2

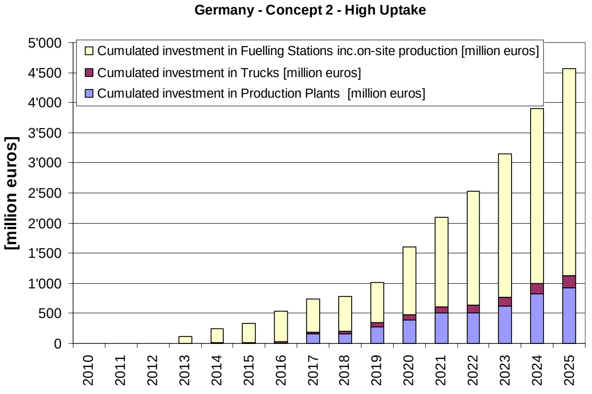


Figure 81: Cumulative annual investment cost in Germany split by production, distribution and transport; high uptake, concept 2, scenario 2

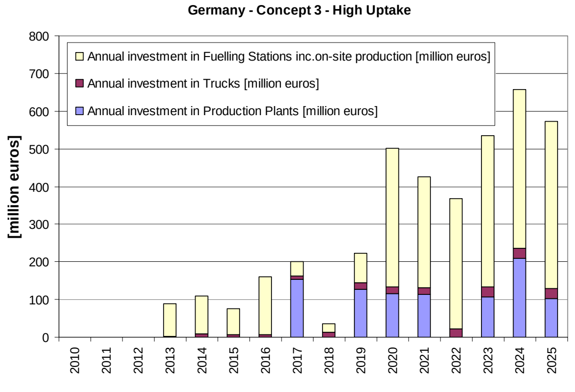


Figure 82: Annual investment cost in Germany split by production, distribution and transport; high uptake, concept 3, scenario 2

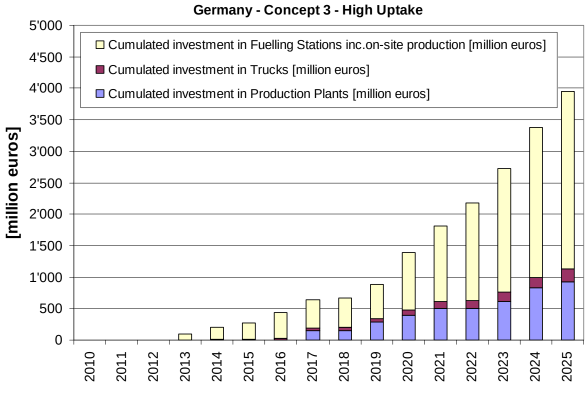


Figure 83: Cumulative annual investment cost in Germany split by production, distribution and transport; high uptake, concept 3, scenario 2

4.14 Investment results

The participation of different actors in this scenario is once again represented by splitting the production and transportation stage into two equal parts, and the distribution stage into three, as a proxy for the different firms that could participate. Figure 84 to Figure 89 illustrate the investment costs and revenues year-by-year, and then cumulated, for Germany under concepts

1-3. Each is for a single actor in the relevant stage of the chain. The assumptions regarding pricing and other issues remain the same as for scenario 1.

As might be expected, the figures indicate that the producers have a more attractive market proposition than the downstream distributors. Once again, the costs for electrolytic hydrogen are high in comparison with the fixed price of hydrogen assumed, and this is the least favourable opportunity.

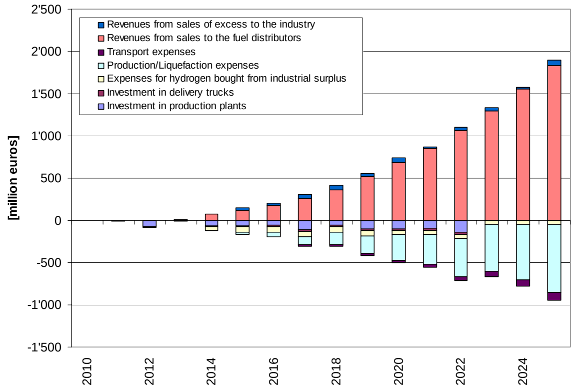


Figure 84: Annual undiscounted costs and revenues for one of two producer/transporters in Germany for concept 1, high uptake, scenario 2

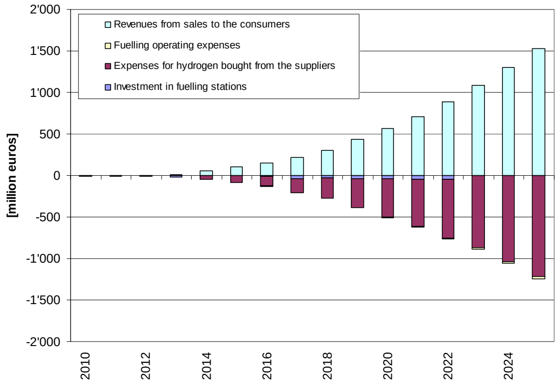


Figure 85: Annual undiscounted costs and revenues for one of three distributors in Germany for concept 1, high uptake, scenario 2

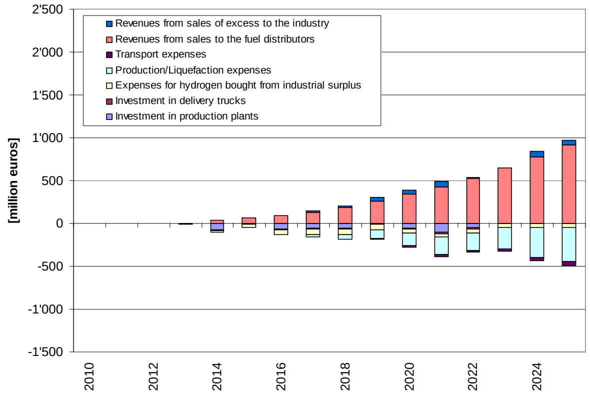


Figure 86: Annual undiscounted costs and revenues for one of two producer/transporters in Germany for concept 2, high uptake, scenario 2

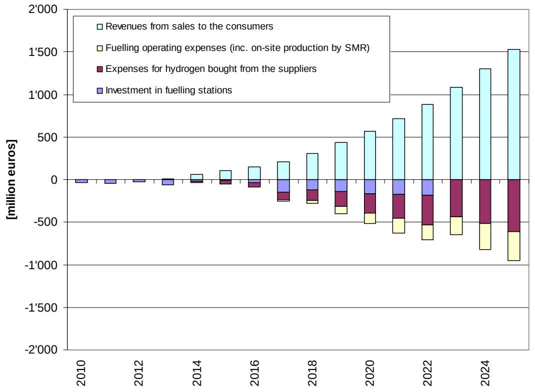


Figure 87: Annual undiscounted costs and revenues for one of three distributors in Germany for concept 2, high uptake, scenario 2

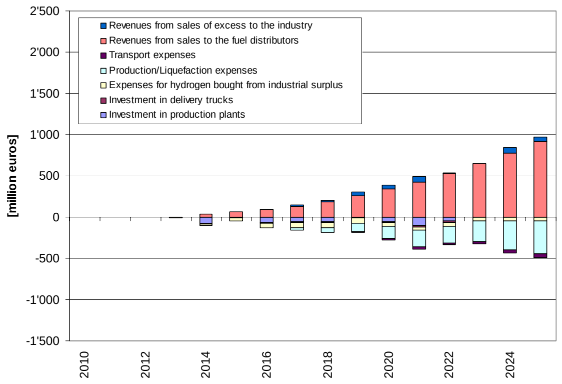


Figure 88: Annual undiscounted costs and revenues for one of two producer/transporters in Germany for concept 3, high uptake, scenario 2

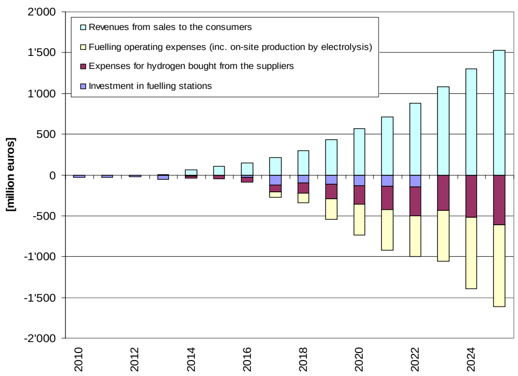


Figure 89: Annual undiscounted costs and revenues for one of three distributors in Germany for concept 3, high uptake, scenario 2

Break-even for the different concepts for a number of countries is illustrated in Figure 90 to Figure 95. In this case, Germany has invested heavily at the beginning and has more rapid demand growth than the other countries, so break-even occurs first, around 2019 for the aggregated producers under each concept. Distributors again typically fare less well, though for the earliest participants break-even occurs before the producers in concept 1, around 2018. Concept 2 has longer timescales, with the first positive results around 2021, and concept 3 shows a tendency towards increased negative results. Once again, the fixed prices of electricity and hydrogen make the potential for positive cashflows very small.

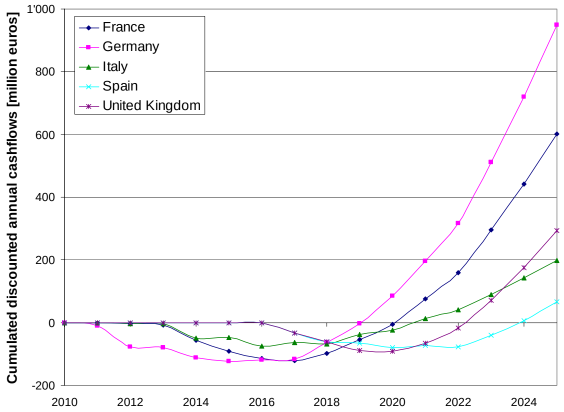


Figure 90: Break-even for one of two producers/transporters in selected EU countries, concept 1, high uptake, scenario 2

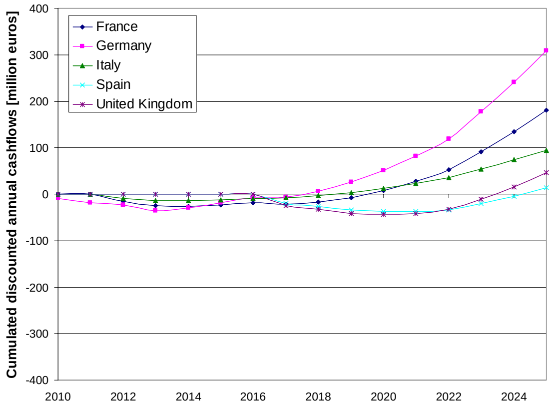


Figure 91: Break-even for one of three distributors in selected EU countries, concept 1, high uptake, scenario 2

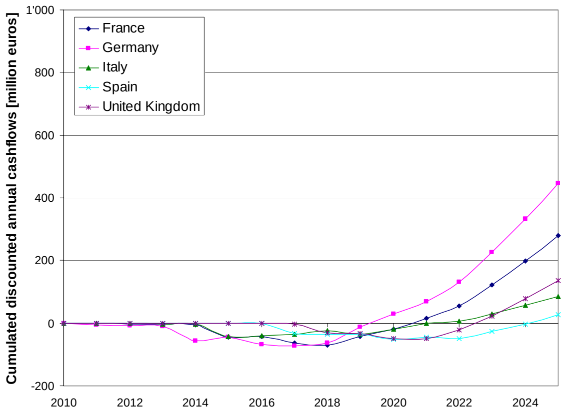


Figure 92: Break-even for one of two producers/transporters in selected EU countries, concept 2, high uptake, scenario 2

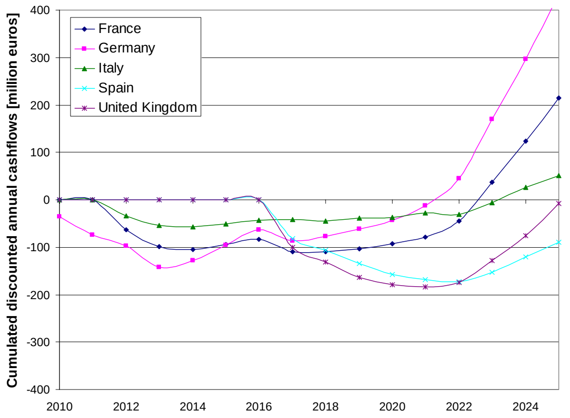


Figure 93: Break-even for one of three distributors in selected EU countries, concept 2, high uptake, scenario 2

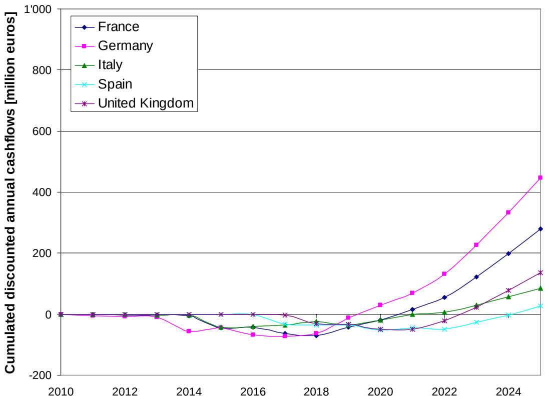


Figure 94: Break-even for one of two producers/transporters in selected EU countries, concept 3, high uptake, scenario 2

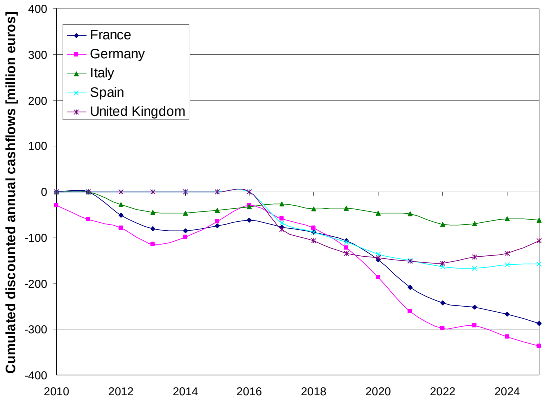


Figure 95: Break-even for one of three distributors in selected EU countries, concept 3, high uptake, scenario 2

Figure 96 and Figure 97 show the picture as if an individual producer and transporter handled the upstream element of hydrogen refuelling, while a single distributor handled the downstream distribution and sales. The producer's cashflow becomes strongly positive after 2021 for concept 1, and only a year later for concepts 2 and 3. Break-even for concept 1 is again earlier for the consolidated distributor, and slightly later for concept 2. Concept 3 fails to break even during the modelling period.

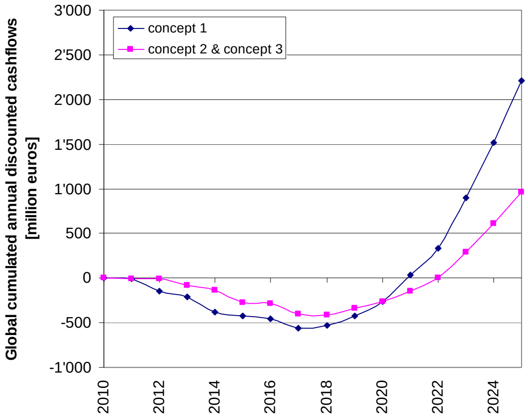


Figure 96: Break-even for one single producer/transporter in Europe, concept 1, 2 and 3, high uptake, scenario 2

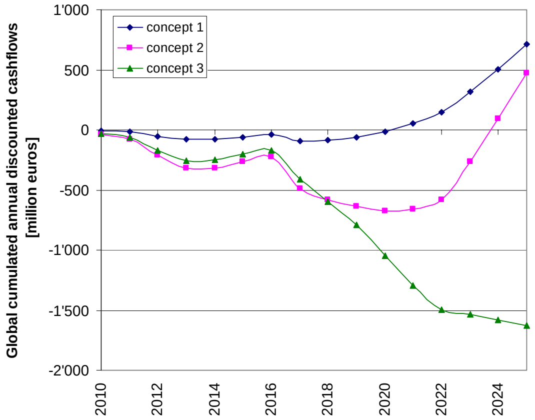


Figure 97: Break-even for one single distributor in Europe, concept 1, 2 and 3, high uptake, scenario 2

Figure 98 demonstrates a positive overall result for the single production and distribution entity in Europe around 2021 for concepts 1 and 2, and in this case concept 3 also shows a positive trend after 2022. This is due to the strong positive contribution of the downstream element of the business.

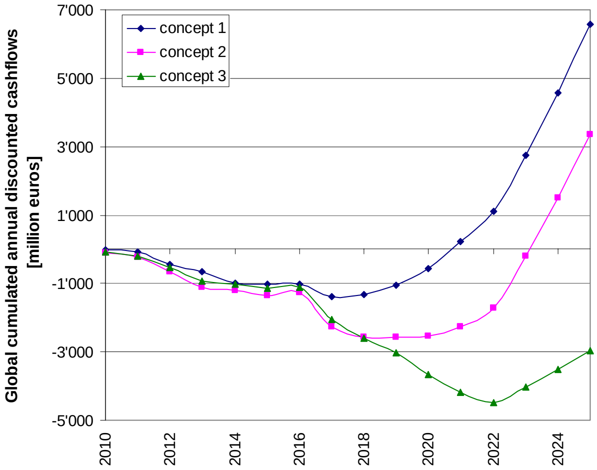


Figure 98: Break-even for one integrated supplier in Europe, concept 1, 2 and 3, high uptake, scenario 2

4.15 Summary

The scenarios analysed for this study indicate that a hydrogen refuelling infrastructure for Europe could be built, for selected demand centres and the links between them, for a sum of between 18 and 32bn Euros for a fleet of 40m hydrogen vehicles in 2030, or between 9 and 15bn Euros for a fleet of 20m vehicles in 2025. Fuelling station costs can be as low as 6bn Euros for the former case, and 3bn for the latter, or as high as 24bn and 11bn, respectively (including 50% on-site production equipment). While most of the cases analysed suggest a timeframe to positive cashflow of around ten years, this varies considerably across the different fuelling concepts considered. In some cases it is not reached within the modelling span.

5 PREVIOUS INFRASTRUCTURE COMPARISONS

The results in the previous section indicate that not only are the investment requirements for the introduction of a hydrogen infrastructure within Europe within plausible limits, but companies are also able to make a positive return over the longer term. Nevertheless, the infrastructure transition required to enable the uptake of hydrogen vehicles – and vice versa – involves a significant amount of capital and is a business risk. However, similar transitions have taken place in energy infrastructures, and in other fields, in the past. Given a suitable framework, investors might be prepared to invest in this infrastructure. In order to put this analysis into perspective, a brief comparison has been made between the type of change suggested here, and infrastructure changes made in the past. These cover not only energy infrastructures, but others sharing similar characteristics to the hydrogen transition.

5.1 Comparison with past transitions

The transition to widespread use of hydrogen in transport is often expected to be hampered by many factors, including high capital costs of infrastructure, uncertain uptake of hydrogen vehicles, and the need for widespread refuelling points. However, infrastructure transitions have happened successfully in the past, some of which shared these ‘difficult’ characteristics. We looked at 28 previous transitions to new types of infrastructure (see Appendix 12), to see how they occurred, and how the difficulties above were overcome. Factors that we considered included consumer response, the scale and types of infrastructure required, how the infrastructure developed over time, and the actors that invested in development. We then chose three transitions where the most interesting comparisons with hydrogen could be made:

- the first gasoline refuelling stations in the US;
- the first electricity networks worldwide; and
- the development of broadband networks in the EU

None of these is a perfect match for hydrogen, but each gives an indication of what can be achieved under uncertain conditions. For each case, implications of interest for hydrogen are given in italics.

5.1.1 Gasoline refuelling stations in the US

When the automobile industry emerged in the 1890s, there were three competing options – electric, steam, and gasoline. Gasoline was not the winner at first. In 1899, steam and electric cars were more popular, as they were cleaner, quieter, and were perceived to be more technically advanced. But in the next 15 years, gasoline emerged as the clear winner, thanks to mass production, lower prices, and technical improvements – from the crank start to an electric starter motor, higher speed and longer range.

At first, drivers had to buy cans of gasoline from grocery stores, hardware stores and blacksmiths, or buy gasoline ladled from barrels at garages, or from mobile tanks. The first ‘filling station’ was not established in the US until 1906 – by which time there were already 140,000 motor vehicles on the road. Networks of standardised stations, with metered dispensing, did not appear until around 1914.

An established refined products distribution network already existed

Kerosene, and some gasoline, for lighting were supplied using tankers refilled from local hubs called bulk stations. These were situated where they could be supplied by rail or by pipeline. For example, by 1906, Standard Oil had 3,573 of these bulk stations across the US.

Hydrogen also has established networks upon which to base infrastructure – the natural gas and electricity grids, and existing industrial hydrogen producers.

Filling stations were developed by diverse players – large and small private companies, each using a different approach

Large companies began to build networks of stations, spreading out over a whole state, and developing consistent designs and branding. However, there remained a large number of small independent stations, using equipment designed in-house, or bought from one of the many gasoline pump manufacturers. Differentiation between stations was based as much upon service (air, water and oil checks, wiping windscreens, selling drinks, station design) as on the product sold.

A role for both small and large players in hydrogen supply could be envisaged, especially as a result of the range of hydrogen generation and distribution technologies available: from smaller players with on-site generation to large organisations with networks based around hydrogen pipelines.

Filling stations encountered early local resistance

Some municipalities were worried that filling stations were unsightly, and also that they were a fire hazard. This resistance was overcome as a result of strong public support, as filling stations were incredibly convenient compared with the existing refuelling options. This relied upon the public being familiar with the car, before addressing the question of siting the station.

Public understanding and familiarity with hydrogen vehicles, such as buses and taxis, and recognition of their benefits, could help to overcome initial doubts over refuelling sites.

5.1.2 Electricity

With Thomas Edison's invention in 1879 of the lightbulb, with a filament made from carbonised bamboo fibre, came huge demand for lighting systems powered by stand-alone generators. Edison, however, realised the economies of scale possible in electricity generation, and planned for complete electricity systems: generators, wires and lamps. The first system started in 1882 in New York, powering lights in Wall St offices.

Systems began to spring up in cities across the world, driven by demand from wealthy patrons and local authorities for these novel, bright electric lamps. The systems did not allow for further growth, however, as this was not possible with Edison's DC system. Growth in rural areas relied on the advent of Westinghouse's AC system, which was also used to bring power from generation sources further away, such as hydroelectric dams. Connections between different networks were not made possible until the 'universal system' was established in 1893.

Electric lighting involved introducing the public to a new energy form

The public accepted using the new energy form readily – there was a rush to adopt electric light in theatres, restaurants and banks, and for local authorities to install electric streetlights. The public also accepted generators – the first steam generators were near to sites of demand, and therefore near to the public – and the emerging networks of wires.

Hydrogen is being introduced to a public that is considerably more technologically literate than that of the 1880s, and considerably more familiar with a range of energy carriers.

Networks were seldom built by private companies alone, and involved cooperation between many players

The technology was developed by pioneer companies, such as Edison's Electric Light Company, the Westinghouse Electric Company, Werner Von Siemens in Germany and Charles Merz of England. At first, these companies aimed to 'own, manufacture, operate and license' systems. The first three mini grids in towns in the UK, established in 1882, were also run by private companies.

However, privately run systems did not grow quickly – the systems were expensive, and few customers could afford the service. Permission from public authorities was also needed to install systems – e.g. putting wires across public land. Involvement from public authorities, such as town councils, allowed use of tax revenues to help overcome high capital costs, and facilitated development of systems for public benefit. Public involvement was not motivated by profit, but by providing a service, savings to the public, and local prestige.

Different options were used in different regions: the US tended towards private ownership with local regulation, in Germany, private companies cooperated with local authorities, in Scandinavia, municipal authorities owned local systems. In the UK, conflict between the private sector, local government and national government, who feared development of monopolies, hampered progress significantly. Local communities set up systems using local waterways for hydroelectricity in areas such as Canada, Japan, New Zealand and Scandinavia. These were financed from taxes, or through issuing bonds, and run as a non-profit service.

Different mixes of public and private, local and national investment were successful in different regions, depending on local markets and conditions. This is also seen in the next example: broadband networks.

Similarly for hydrogen, one model of infrastructure investment is unlikely to suit all regions, though cooperation with public bodies at a local level could speed development. The range of hydrogen production, transport and storage technologies available, and the range of scale at which they can be used, facilitates market entry from a range of players.

Different types of system coexisted, and still do today

For towns, Edison's DC systems were simple, and less expensive to the customer. DC could not be used to cover long distances, so Westinghouse's AC system was more suitable for rural areas, and to bring power from generation sources further away, such as hydroelectric dams. Connections between these networks were made possible by the 'universal system' from 1893 – this avoided emerging problems of overlapping networks, and of local monopolies. However, networks today still vary between countries (frequencies and voltages) and involve a range of generation, transmission and distribution technologies and scales.

Whilst standardisation at some levels is essential for hydrogen – being able to refuel with the required hydrogen pressure, for example, with standard refuelling equipment – complete convergence across all regions is likely to be unnecessary, and not give the optimum systems for each region.

In several cases, the electricity provider also supplied the appliance

Edison originally supplied both electricity and the lamps to run from it. The Tennessee Valley Authority extended electricity grids to US farmers, helped to design appliances suitable for them, and helped them to buy the appliances.

The development of a contractual link between hydrogen refuelling stations and vehicles – not just for fleet vehicles, but also for private customers – would enable significant reduction of risk both for consumer and provider. If vehicles were leased including a certain amount of fuel provision, for example, consumer take-up might be more positive than without any support.

5.1.3 Broadband internet development in the EU

Definitions of broadband vary, but it is generally taken to mean a high-speed data connection, which is continuously connected – 'always-on'. Broadband allows fast Internet access, and so enables services for business and domestic use, such as electronic trading, videoconferencing and interactive multimedia services. Broadband coverage in several EU countries is now reaching over 90% of the population, with uptake generally at around 10-20%.

Broadband has overcome its own ‘chicken and egg’ problem

Operators would not invest in broadband infrastructure while there was no new content to motivate the user to upgrade – streaming video services, online trading etc. Equally, no real push existed to develop these new applications and content as long as the supporting infrastructure was inadequate.

This was overcome by policies aimed at developing content, including public procurement of new services, together with demonstrating the benefits of the content, for example through promotion of public open access to broadband using wireless networks.

The often quoted ‘chicken and egg’ problem of hydrogen use in vehicles and hydrogen infrastructure development is also being approached through use in early niche applications. Further activity and innovative policies in this area could lead to the ‘virtuous circle’ that has overcome the problem in broadband development. Further development in providing the consumer a measurable personal benefit will aid in the introduction of hydrogen vehicles, and this area is likely to be strongly influenced by policy in the short term.

Different broadband technologies can be used depending on the density of consumers, and on the existing infrastructure

In most EU countries, a combination of technologies is used. For example, in the UK, the technologies used are DSL, cable modem, satellite, optical fibre, and wireless. The most widespread technologies, such as DSL use existing physical connections. Technologies that need a new physical link to the customer, such as optical fibres, are used where there is a high density of customers, and/or a faster service is required. For more remote areas, technologies with no physical link can be used –satellite and fixed wireless access (radio). Other options include a combination of infrastructure types, for example a main network of optical fibres, with wireless transmitters to cover the ‘last mile’ to the consumer.

This is analogous to the range of options for hydrogen. Existing infrastructure, such as the natural gas network or electricity network can be used at first. Dedicated hydrogen pipelines can be used to supply new, high density, or heavy demand, and use of these pipelines increased as uptake increases. Distributed hydrogen generation can be used for remote areas, or for extra generation in areas of high/new demand. Combined infrastructures can also be compared – hydrogen pipelines to a regional hub, followed by road tanker delivery to refuelling stations. The rapid development of broadband coverage in the EU has been enabled by having this range of options, and they will be essential to improving broadband services – hydrogen technology diversity could do the same.

Broadband coverage radiated from cities, but also sprang up in niche markets

Coverage by one or more of the options described above is available in most large EU15 cities, with networks growing out into the suburbs, and beginning in new, smaller cities. Patches of high-speed coverage have emerged in niche areas: optical fibre local area networks in universities and business parks, where there are significant benefits of early adoption.

This is very similar to the development model suggested for hydrogen – radiating networks of stations from urban centres, plus availability linked to niche users

Broadband has been strategically planned at an EU and national level, including targets for coverage and uptake

The eEurope 2005 Action Plan, published in 2002, set an ambitious target: 'widespread broadband availability and use in the EU by 2005’. Further targets included: all public administrations to have broadband connections by the end of 2005, and half of all internet connections to be broadband by 2005. Getting widespread broadband use is seen as essential for ‘eHealth, eBusiness, eGovernment and eLearning, making broadband crucial to European growth and quality of life in the years ahead.’

The Commission helped Member States to develop and implement national strategies, through information events, workshops, strategic documents and new regulatory frameworks. EU Structural funds could also be used for broadband-related projects. All EU 15 countries developed national strategies. For example, the UK aims to have the most extensive and competitive broadband market in the G7 by 2005. It has supported this through a new Broadband Stakeholder Group, demand-side measures, and work with regional bodies.

Recognising and stating the strategic importance of hydrogen at an EU level, together with setting clear targets, and cooperating on strategic plans, could speed hydrogen infrastructure development in the same way.

Innovative demand-side policies are being used in all EU15 countries

These policies help to match demand and supply, and involve local governments, broadband users and other stakeholders. In the UK, broadband brokerage services have been set up to gather potential broadband customers in a local area, to persuade suppliers to extend coverage to their area, based around public sector demand nodes. In Portugal, the e-U initiative used public-private partnerships, with some EU support, to install WiFi networks in every university, and to provide wireless laptops to users at reduced prices.

These types of approach could stimulate and aggregate demand for hydrogen, to encourage investment in supply options.

In many countries, limited supply-side support has been evident

In most urban areas, and therefore for most of the population, infrastructure has mainly been financed by the private sector. Competitive markets, new regulatory frameworks, and a range of technology availability have helped communications service companies invest in these areas with little additional financial support. These companies ranged from very large ex-national telecommunications suppliers, to small cable and satellite companies. A range of models was used, from installation of networks alone, with competition for service provision, to combined infrastructure and service companies.

The majority of this fast and widespread network growth has been made based on private investment, from companies who were not all very large telecommunications players. Given a strong driver for hydrogen uptake, large and small players with a range of technologies could develop hydrogen infrastructure, and not just the major existing energy providers.

Rural areas have needed more support in many cases

Broadband networks involve high levels of investment, but communication service providers have little capital, and so need the prospect of significant returns to be able to finance expansion into a new area. For example, in Sweden, the Government invested 0.6bn Euros of the 4.4bn Euros estimated for full expansion of optical fibre networks to rural areas. The subsidy was administered via municipalities, and the networks built by private companies or by the municipality. In many countries, municipalities have built fibre optic networks in rural areas to stimulate investment.

For areas where new infrastructure was not competitive, regions developed new models of public-private cooperation, which could potentially be applied to hydrogen refuelling network development.

5.2 Cost implications

Limited data exist on the cost of infrastructure developments, in part because they were never financed as ‘an infrastructure’. Nevertheless, the first investments were very large.

Edison's first electric system – Manhattan real estate, the power station and all the wires, underground conduits, and other fixtures – cost about $300,000 to build in 1882. Using the GDP deflator as a means of adjusting prices, this represents close to $5m today, or approximately 3.8m Euros.

For broadband, the costs are also high. As discussed above, in Sweden, the cost of a full expansion of optic fibre in rural areas is estimated at around 4.4bn Euros. In Ireland, a 152m Euro subsidy was introduced to roll out 880m Euros worth of broadband capacity to every parish in the country.

5.3 Possible actors

Different stakeholders and actors will have to invest in the hydrogen energy supply chain in order for a sustainable industry to develop. In this section the actors relevant to the supply-side are briefly considered. The customer, who has bought the vehicle and wishes to buy the fuel, is not discussed here, though in many ways they may be the most important part of the chain.

5.3.1 Hydrogen producers and suppliers

Each country considered has a very wide range of possible actors who could operate within the risk/reward profile suggested. In the UK alone, the four largest road fuel marketers have an approximate equal market presence with approximately 1,400 fuelling stations each. Over the past decade, the amount of fuel sold by supermarkets has increased enormously, and the major chains in France now account for over 50% of sales to consumers. This suggests that in most countries 6-8 actors possess the financial muscle and existing logistics know-how to participate in hydrogen fuel provision on a large scale, and typically many others may be able to operate on a smaller regional or local basis.

The potential for supermarkets to enter the supply chain for hydrogen is intriguing. They not only have massive purchasing power, and could thus potentially introduce hydrogen at a more competitive cost than smaller competitors, they also have significant fleets of vehicles. This analysis has been focused on passenger cars rather than fleets, but the latter offer a promising opportunity for controlled introduction of hydrogen as a fuel. A hypothetical scenario: If the supermarkets could fuel their own fleets at their own fuelling stations, they could guarantee a certain level of demand and hence remove some of the risk of investing in infrastructure provision. Providing hydrogen to private consumers would then be an additional service. Whether or not this would be an attractive investment for a retail organisation is not clear from this analysis.

From the production side, the industrial gas companies are possible investors, as transport fuelling offers the potential to significantly expand their hydrogen markets. However, the margins on providing hydrogen as a fuel are likely to be considerably lower than the provision of the industrial chemical. Nevertheless, this analysis suggests that profits can be made if the conditions are right.

Other companies could also produce the hydrogen required, including petroleum refiners . However, it is unlikely in the short term that they would do so without joint agreements with the gas companies, for example, which already provide them with hydrogen for their refinery operations. In any case, as we have noted, some industrial surplus of hydrogen exists in the early stages of these scenarios, and so new production facilities would not be required.

On-site production would probably also include equipment developed by much smaller entrants to the hydrogen energy sector, in addition to existing hydrogen suppliers. These companies are already beginning to enter the market. Conceivably, natural gas companies may also wish to add value to their commodity by moving downstream.

5.3.2 Regulatory and legislative bodies

The actors who create policy frameworks for hydrogen are also critical to the emergence of a market. In order for hydrogen to be competitive with conventional fuels, and for consumers to be attracted to it, some form of government support is very likely to be required. This may be in the form of enabling legislation, such as allowing hydrogen vehicles on public roads, or more targeted support. The California ZEV mandate has accelerated the development of hydrogen vehicles considerably, and Japan is in the process of developing support packages for early hydrogen infrastructure and vehicle providers. Local authorities can also play a role by providing incentives such as free parking – London already exempts low-emission vehicles from its congestion charge.

The government can also mitigate some risk in terms of setting clear and long-term targets. The provision of, for example, a ten year tax break for hydrogen fuel allows corporate planning to take place in an environment where some of the variables are known. The absolute level of a support mechanism may be less important than its flexibility, or its longevity. Businesses tend to favour market-based instruments over direct regulation as they are then able to apply strategies that most suit their existing business, though in some cases these may not adequately satisfy the policy objective to be met.

5.3.3 Other actors

A further important component of the investment framework is the education, training and standards sector. Public acceptance of hydrogen technologies will be crucial if they are to be successful. Equally, suitable support services will be required, and codes and standards must be in place to allow the development of infrastructure. While these actors are not included in the scenario development above, their influence will be very important in each country or region if they are to be successful.

6 CONCLUSIONS

This study has analysed two conceptual scenarios for the development of hydrogen infrastructure in Europe, using possible hydrogen vehicle penetration rates from an external source as one input. The timescale selected is from 2010 to 2030, when hydrogen vehicles could enter volume production and be introduced into showrooms, and when initial hydrogen infrastructures will be proven. The scenarios are not intended to be predictions of the future.

A key result of the modelling is that allocating a hydrogen infrastructure in stages, according to concentrated vehicle demand, is potentially within the cost and risk horizons of major actors, such as energy companies. Developing a hydrogen fuelling station infrastructure to supply a fleet of 40m hydrogen vehicles in certain areas of Europe by 2030 could cost in the region of 6bn Euros, plus approximately 11bn Euros for the production and distribution capacity under a centralised scenario. Decentralised scenarios benefit less from economies of scale, and have total costs of 25-30bn Euros, with a considerably greater proportion spent on-site at the fuelling station.

A scenario in which the infrastructure development is considered slightly more strategically, and links countries and cities with a major automotive company presence, suggests that centralisation can improve the economics of the investment. This is due to the fact that the number of hydrogen vehicles introduced is considered to be the same in each scenario, but put into fewer regions in the second. This higher level of demand means that the ratio of revenue to cost is greater for those regions, and payback times shorter.

In each case, the investment takes place in stages over a period of time, and revenues are generated early on in as hydrogen vehicles are introduced. This results in cashflows that can become positive in less than ten years for some scenarios. Some major corporations may view this timescale as well within their horizons for a major infrastructure project. However, risk will need to be managed carefully as hydrogen vehicle uptake is a key uncertainty.

No explicit government support has been assumed, whether local or national. Possible mechanisms would include enhanced capital recovery factors, incentives for the purchase of hydrogen vehicles, zero emissions zones in cities, or other regulatory or market mechanisms. However, the selling price for hydrogen is set equivalent to the price of taxed gasoline, giving an implicit tax exemption for the period of the analysis. Equally, the gasoline price is assumed to remain constant over the period. Given the uncertainty associated with long-term energy prices, these factors should act to cancel each other out to some extent. Nevertheless, once hydrogen has been successfully introduced into the market it seems highly unlikely that it would remain exempt from duty.

Government support is likely to be very important in minimising risk within all scenarios. Supportive and predictable policy frameworks will enable companies to make decisions on the basis of a known future – at least for some timeframe. Specific support for vehicles or infrastructure would provide greater incentives.

The different concepts for fuelling stations – fully centralised hydrogen production, or partially decentralised – have markedly different investment and revenue profiles. Within the limitations of the model it has not been possible to represent all local variables in fine detail, and so the electrolysis option, for example, appears to be quite unprofitable. This is due, in part, to high electricity prices in comparison with natural gas, and an assumption that final hydrogen selling prices are fixed and constant. In practice, local conditions will play a major part in an investment decision, and individual stations based on electrolytic production of hydrogen may be very attractive in some regions.

This analysis considers only the cost implications of developing a hydrogen infrastructure to supply passenger cars. Any future introduction of hydrogen will certainly be influenced heavily by policy, which will include both energy supply/resource considerations, and environmental implications, amongst other factors. None of these is modelled here, though CO_2 emissions from transport are currently a major consideration.

Although the costs of the scenarios are considerable, they are quite low in comparison with other infrastructure transitions and investments, and should be well within the range of investments for many large corporations. A variety of actors could potentially participate in the development of such an infrastructure, including existing refiners and marketers of fuels, other forecourt operators such as supermarkets, and industrial hydrogen suppliers. Enough of these actors exist across Europe for the risk to be shared as required.

In summary, it appears that the costs and returns associated with developing an initial hydrogen infrastructure are not obviously prohibitive. A significant fleet of passenger cars could be fuelled in a set of European countries for approximately the same cost as the mobile phone network licences auctioned in the UK in 2000. Previous energy and infrastructure transitions have also been typically expensive and risky.

Nevertheless, considerable business risk is involved in such an undertaking, and so a supportive policy framework and the fit of the risk with individual corporate strategies will be essential. The development of the infrastructure in a suitably co-ordinated fashion would allow more rapid payback and also minimise some of the risks.

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8 APPENDICES

APPENDIX 1: List of urban areas considered and their respective population in million inhabitants [Wikipedia Encyclopedia]

Scenario 1

Amsterdam	2.1	London	11.9
Antwerp	1.2	Lyon	1.7
Athens	3.5	Madrid	5.6
Barcelona	3.8	Mannheim	1.7
Budapest	2.6	Milan	3.8
Berlin	4.2	Munich	1.9
Birmingham	2.6	Napoli	3.0
Brussels	2.5	Newcastle	1.0
Copenhagen	1.8	Oporto	1.3
Dublin	1.0	Île de France	11.3
Düsseldorf	1.4	Prague	1.3
Frankfurt	2.0	Rome	3.3
Glasgow	1.6	Rotterdam	1.2
Hamburg	2.6	Ruhr Area	6.1
Hanover	1.0	Sevilla	1.2
Helsinki	1.2	Sheffield	1.4
Kassel	1.3	Stockholm	1.7
Köln	1.9	Stuttgart	2.7
Leeds	2.1	Torino	1.5
Lille	1.8	Toulouse	1.0
Lisbon	2.9	Gdansk	1.0
Liverpool	1.4	Valencia	1.4
Lodz	1.1	Vienna	1.9
		Warsaw	2.4

Scenario 2

Amsterdam	2.1	Madrid	5.6
Barcelona	3.8	Milan	3.8
Berlin	4.2	Prague region (Mlada Boleslav)	0.05
Bern	0.13	Munich	1.9
Brussels	2.5	Posen	0.58
Frankfurt	2.0	Stuttgart	2.7
Hamburg	2.6	Torino	1.5
Île de France	11.3	Warsaw	2.4
Köln	1.9	Wolfsburg	0.12
London	11.9	Zaragoza	0.66
Lyon	1.7	Zürich	1.09

APPENDIX 2: Number of passenger cars per inhabitant, on a country basis [Eurostat, 2001]

Scenario 1

Amsterdam	0.418	London	0.464
Antwerp	0.455	Lyon	0.485
Athen	0.322	Madrid	0.451
Barcelona	0.451	Mannheim	0.539
Budapest	0.244	Milan	0.574
Berlin	0.539	Munich	0.539
Birmingham	0.464	Napoli	0.574
Brussels	0.455	Newcastle	0.464
Copenhagen	0.350	Oporto	0.364
Dublin	0.359	Île de France	0.485
Düsseldorf	0.539	Prague	0.344
Frankfurt	0.539	Rome	0.574
Glasgow	0.464	Rotterdam	0.418
Hamburg	0.539	Ruhr Area	0.539
Hanover	0.539	Sevilla	0.451
Helsinki	0.414	Sheffield	0.464
Kassel	0.539	Stockholm	0.452
Köln	0.539	Stuttgart	0.539
Leeds	0.464	Torino	0.574
Lille	0.485	Toulouse	0.485
Lisbon	0.364	Gdansk	0.272
Liverpool	0.464	Valencia	0.451
Lodz	0.272	Vienna	0.514
		Warsaw	0.272

Scenario 2

Amsterdam	0.418	Madrid	0.451
Barcelona	0.451	Milan	0.574
Berlin	0.539	Mlada Boleslav	0.344
Bern	0.502	Munich	0.539
Brussels	0.455	Posen	0.272
Frankfurt	0.539	Stuttgart	0.539
Hamburg	0.539	Torino	0.574
Île de France	0.485	Warsaw	0.272
Köln	0.539	Wolfsburg	0.539
London	0.464	Zaragoza	0.451
Lyon	0.485	Zürich	0.502

APPENDIX 3: Fuelling station investment cost [M. Wilhelm, 2004]

Scenario 1

Concept 1 – High Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser							
	Number of 'standard' fuelling stations		Liquid H2 tank (50%) [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	Liquid H2 tank (50%) [euros]	Cryogenic pump [euros]	High pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.95	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0													
2011	0													
2012	0		135000	90000	70000	70000	135000	110000	20000	40000	15000	70000	50000	805'000
2013	297		92327.79	26082.39	33940.19	20286.30	92327.79	31878.48	9697.20	27356.38	10258.64	33940.19	14490.22	392'586
2014	654		88627.17	24271.40	31689.21	18877.75	88627.17	29665.04	9054.06	26259.90	9847.46	31689.21	13484.11	372'092
2015	885		87262.84	23689.41	30894.19	18425.10	87262.84	28953.73	8826.91	25855.66	9695.87	30894.19	13160.79	364'922
2016	1464		85058.82	22838.08	29649.47	17762.95	85058.82	27913.21	8471.28	25202.61	9450.98	29649.47	12687.82	353'744
2017	1565		84773.64	22735.54	29491.97	17683.20	84773.64	27787.88	8426.28	25118.11	9419.29	29491.97	12630.86	352'332
2018	1595		84691.37	22706.28	29446.70	17660.44	84691.37	27752.11	8413.34	25093.74	9410.15	29446.70	12614.60	351'927
2019	1815		84143.00	22514.74	29146.62	17511.46	84143.00	27518.02	8327.60	24931.26	9349.22	29146.62	12508.19	349'240
2020	2791		82352.02	21930.69	28187.59	17057.21	82352.02	26804.18	8053.60	24400.60	9150.22	28187.59	12183.72	340'659
2021	3738		81167.21	21577.58	27570.83	16782.56	81167.21	26372.60	7877.38	24049.54	9018.58	27570.83	11987.54	335'142
2022	4888		80103.19	21281.76	27028.93	16552.48	80103.19	26011.05	7722.55	23734.28	8900.35	27028.93	11823.20	330'290
2023	6225		79161.46	21036.00	26558.76	16361.33	79161.46	25710.66	7588.22	23455.25	8795.72	26558.76	11686.66	326'074
2024	7654		78369.80	20840.58	26170.37	16209.34	78369.80	25471.82	7477.25	23220.68	8707.76	26170.37	11578.10	322'586
2025	9427		77583.87	20656.30	25790.99	16066.01	77583.87	25246.59	7368.85	22987.81	8620.43	25790.99	11475.72	319'171
2026	11178		76950.00	20514.51	25489.49	15955.73	76950.00	25073.29	7282.71	22800.00	8550.00	25489.49	11396.95	316'452
2027	13009		76392.45	20394.67	25227.61	15862.52	76392.45	24926.82	7207.89	22634.80	8488.05	25227.61	11330.37	314'085
2028	14901		75898.60	20292.24	24998.23	15782.85	75898.60	24801.62	7142.35	22488.47	8433.18	24998.23	11273.47	312'008
2029	16753		75476.50	20207.39	24804.11	15716.86	75476.50	24697.93	7086.89	22363.41	8386.28	24804.11	11226.33	310'246
2030	18628		75097.41	20133.28	24631.28	15659.22	75097.41	24607.34	7037.51	22251.08	8344.16	24631.28	11185.15	308'675

Concept 1 – Low Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser							
	Number of 'standard' fuelling stations		Liquid H2 tank (50%) [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	Liquid H2 tank (50%) [euros]	Cryogenic pump [euros]	High pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.95	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0													
2011	0													
2012	0		135000	90000	70000	70000	135000	110000	20000	40000	15000	70000	50000	805'000
2013	0		135000.00	90000.00	70000.00	70000.00	135000.00	110000.00	20000.00	40000.00	15000.00	70000.00	50000.00	805'000
2014	0		135000.00	90000.00	70000.00	70000.00	135000.00	110000.00	20000.00	40000.00	15000.00	70000.00	50000.00	805'000
2015	0		135000.00	90000.00	70000.00	70000.00	135000.00	110000.00	20000.00	40000.00	15000.00	70000.00	50000.00	805'000
2016	409		90805.82	25294.61	32997.67	19673.59	90805.82	30915.64	9427.91	26905.43	10089.54	32997.67	14052.56	383'966
2017	759		87948.59	23976.48	31291.44	18648.37	87948.59	29304.58	8940.41	26058.84	9772.07	31291.44	13320.26	368'501
2018	820		87605.12	23831.34	31091.88	18535.48	87605.12	29127.19	8883.39	25957.07	9733.90	31091.88	13239.63	366'702
2019	839		87498.12	23786.68	31029.95	18500.75	87498.12	29072.61	8865.70	25925.37	9722.01	31029.95	13214.82	366'144
2020	1027		86601.46	23422.73	30515.54	18217.68	86601.46	28627.78	8718.73	25659.69	9622.38	30515.54	13012.63	361'516
2021	1342		85432.47	22975.00	29857.04	17869.44	85432.47	28080.55	8530.58	25313.32	9492.50	29857.04	12763.89	355'604
2022	1940		83860.87	22418.57	28993.41	17436.67	83860.87	27400.47	8283.83	24847.67	9317.87	28993.41	12454.76	347'868
2023	2788		82355.56	21931.79	28189.45	17058.06	82355.56	26805.52	8054.13	24401.65	9150.62	28189.45	12184.33	340'676
2024	3634		81281.01	21610.39	27629.46	16808.08	81281.01	26412.70	7894.13	24083.26	9031.22	27629.46	12005.77	335'666
2025	4617		80327.29	21342.44	27142.12	16599.68	80327.29	26085.21	7754.89	23800.68	8925.25	27142.12	11856.91	331'304
2026	5639		79544.02	21134.06	26748.69	16437.60	79544.02	25830.52	7642.48	23568.60	8838.22	26748.69	11741.14	327'778
2027	6780		78832.77	20953.64	26396.74	16297.28	78832.77	25610.01	7541.93	23357.86	8759.20	26396.74	11640.91	324'620
2028	7924		78238.01	20809.01	26106.32	16184.79	78238.01	25433.24	7458.95	23181.63	8693.11	26106.32	11560.56	322'010
2029	9198		77675.65	20677.34	25834.97	16082.37	77675.65	25272.30	7381.42	23015.01	8630.63	25834.97	11487.41	319'568
2030	10718		77105.37	20548.71	25563.02	15982.33	77105.37	25115.09	7303.72	22846.04	8567.26	25563.02	11415.95	317'116

Concept 2 – High Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser											
	Number of 'standard' fuelling stations		Liquid H2 tank [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	SMR & PSA	Electric control unit	Compressor 15-400 bars	Intermediate storage 400 bars	Compressor 400-850 bars	Cryogenic pump [euros]	Hign pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.9	0.85	0.9	0.95	0.9	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0																	
2011	0																	
2012	0		210000	90000	70000	70000	1852000	500000	125000	145000	59000	110000	6000	40000	15000	70000	50000	3'412'000
2013	297		143621.00	26082.39	33940.19	20286.30	897960.58	181341.30	60607.49	99166.88	28606.74	31878.48	2909.16	27356.38	10258.64	33940.19	14490.22	1'612'446
2014	654		137864.49	24271.40	31689.21	18877.75	838405.92	167618.98	56587.87	95192.15	26709.48	29665.04	2716.22	26259.90	9847.46	31689.21	13484.11	1'510'879
2015	885		135742.20	23689.41	30894.19	18425.10	817372.00	162988.78	55168.20	93726.76	26039.39	28953.73	2648.07	25855.66	9695.87	30894.19	13160.79	1'475'254
2016	1464		132313.73	22838.08	29649.47	17762.95	784440.13	155974.95	52945.47	91359.48	24990.26	27913.21	2541.38	25202.61	9450.98	29649.47	12687.82	1'419'720
2017	1565		131870.10	22735.54	29491.97	17683.20	780273.38	155108.41	52664.24	91053.16	24857.52	27787.88	2527.88	25118.11	9419.29	29491.97	12630.86	1'412'714
2018	1595		131742.13	22706.28	29446.70	17660.44	779075.48	154860.17	52583.39	90964.81	24819.36	27752.11	2524.00	25093.74	9410.15	29446.70	12614.60	1'410'700
2019	1815		130889.11	22514.74	29146.62	17511.46	771136.19	153224.92	52047.53	90375.81	24566.43	27518.02	2498.28	24931.26	9349.22	29146.62	12508.19	1'397'364
2020	2791		128103.14	21930.69	28187.59	17057.21	745763.05	148116.83	50334.98	88452.16	23758.11	26804.18	2416.08	24400.60	9150.22	28187.59	12183.72	1'354'846
2021	3738		126260.11	21577.58	27570.83	16782.56	729445.44	144928.66	49233.63	87179.60	23238.27	26372.60	2363.21	24049.54	9018.58	27570.83	11987.54	1'327'579
2022	4888		124604.96	21281.76	27028.93	16552.48	715108.31	142191.48	48265.95	86036.76	22781.53	26011.05	2316.77	23734.28	8900.35	27028.93	11823.20	1'303'667
2023	6225		123140.04	21036.00	26558.76	16361.33	702668.87	139866.05	47426.35	85025.27	22385.24	25710.66	2276.47	23455.25	8795.72	26558.76	11686.66	1'282'951
2024	7654		121908.58	20840.58	26170.37	16209.34	692393.30	137980.36	46732.81	84174.97	22057.89	25471.82	2243.17	23220.68	8707.76	26170.37	11578.10	1'265'860
2025	9427		120686.03	20656.30	25790.99	16066.01	682355.86	136169.62	46055.34	83330.83	21738.12	25246.59	2210.66	22987.81	8620.43	25790.99	11475.72	1'249'181
2026	11178		119699.99	20514.51	25489.49	15955.73	674379.09	134752.95	45516.95	82650.00	21484.00	25073.29	2184.81	22800.00	8550.00	25489.49	11396.95	1'235'937
2027	13009		118832.69	20394.67	25227.61	15862.52	667450.46	133538.67	45049.30	82051.15	21263.27	24926.82	2162.37	22634.80	8488.05	25227.61	11330.37	1'224'440
2028	14901		118064.48	20292.24	24998.23	15782.85	661381.86	132487.66	44639.70	81520.71	21069.94	24801.62	2142.71	22488.47	8433.18	24998.23	11273.47	1'214'375
2029	16753		117407.88	20207.39	24804.11	15716.86	656245.92	131607.40	44293.06	81067.35	20906.32	24697.93	2126.07	22363.41	8386.28	24804.11	11226.33	1'205'860
2030	18628		116818.20	20133.28	24631.28	15659.22	651673.32	130830.88	43984.43	80660.18	20760.65	24607.34	2111.25	22251.08	8344.16	24631.28	11185.15	1'198'282

Concept 2 – Low Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser											
	Number of 'standard' fuelling stations		Liquid H2 tank [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	SMR & PSA	Electric control unit	Compressor 15-400 bars	Intermediate storage 400 bars	Compressor 400-850 bars	Cryogenic pump [euros]	Hign pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.9	0.85	0.9	0.95	0.9	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0																	
2011	0																	
2012	0		210000	90000	70000	70000	1852000	500000	125000	145000	59000	110000	6000	40000	15000	70000	50000	3'412'000
2013	0		210000.00	90000.00	70000.00	70000.00	1852000.00	500000.00	125000.00	145000.00	59000.00	110000.00	6000.00	40000.00	15000.00	70000.00	50000.00	3'412'000
2014	0		210000.00	90000.00	70000.00	70000.00	1852000.00	500000.00	125000.00	145000.00	59000.00	110000.00	6000.00	40000.00	15000.00	70000.00	50000.00	3'412'000
2015	0		210000.00	90000.00	70000.00	70000.00	1852000.00	500000.00	125000.00	145000.00	59000.00	110000.00	6000.00	40000.00	15000.00	70000.00	50000.00	3'412'000
2016	409		141253.49	25294.61	32997.67	19673.59	873024.14	175487.29	58924.42	97532.17	27812.32	30915.64	2828.37	26905.43	10089.54	32997.67	14052.56	1'569'789
2017	759		136808.91	23976.48	31291.44	18648.37	827882.08	165287.93	55877.57	94463.30	26374.21	29304.58	2682.12	26058.84	9772.07	31291.44	13320.26	1'493'040
2018	820		136274.63	23831.34	31091.88	18535.48	822602.26	164129.31	55521.21	94094.39	26206.01	29127.19	2665.02	25957.07	9733.90	31091.88	13239.63	1'484'101
2019	839		136108.19	23786.68	31029.95	18500.75	820963.89	163771.27	55410.63	93979.47	26153.82	29072.61	2659.71	25925.37	9722.01	31029.95	13214.82	1'481'329
2020	1027		134713.39	23422.73	30515.54	18217.68	807354.00	160824.41	54492.04	93016.39	25720.24	28627.78	2615.62	25659.69	9622.38	30515.54	13012.63	1'458'330
2021	1342		132894.95	22975.00	29857.04	17869.44	789932.04	157124.31	53316.15	91760.80	25165.22	28080.55	2559.18	25313.32	9492.50	29857.04	12763.89	1'428'961
2022	1940		130450.25	22418.57	28993.41	17436.67	767082.76	152396.77	51773.94	90072.79	24437.30	27400.47	2485.15	24847.67	9317.87	28993.41	12454.76	1'390'562
2023	2788		128108.64	21931.79	28189.45	17058.06	745812.38	148126.59	50338.31	88455.97	23759.68	26805.52	2416.24	24401.65	9150.62	28189.45	12184.33	1'354'929
2024	3634		126437.12	21610.39	27629.46	16808.08	730996.53	145228.40	49338.32	87301.82	23287.69	26412.70	2368.24	24083.26	9031.22	27629.46	12005.77	1'330'168
2025	4617		124953.56	21342.44	27142.12	16599.68	718103.02	142758.21	48468.08	86277.46	22876.93	26085.21	2326.47	23800.68	8925.25	27142.12	11856.91	1'308'658
2026	5639		123735.14	21134.06	26748.69	16437.60	707693.91	140799.85	47765.52	85436.17	22545.32	25830.52	2292.74	23568.60	8838.22	26748.69	11741.14	1'291'316
2027	6780		122628.75	20953.64	26396.74	16297.28	698382.42	139075.53	47137.04	84672.23	22248.68	25610.01	2262.58	23357.86	8759.20	26396.74	11640.91	1'275'820
2028	7924		121703.57	20809.01	26106.32	16184.79	690698.76	137672.49	46618.44	84033.42	22003.90	25433.24	2237.68	23181.63	8693.11	26106.32	11560.56	1'263'043
2029	9198		120828.80	20677.34	25834.97	16082.37	683519.61	136377.97	46133.88	83429.41	21775.19	25272.30	2214.43	23015.01	8630.63	25834.97	11487.41	1'251'114
2030	10718		119941.69	20548.71	25563.02	15982.33	676324.54	135096.63	45648.25	82816.88	21545.98	25115.09	2191.12	22846.04	8567.26	25563.02	11415.95	1'239'167

Concept 3 – High Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser														
	Number of 'standard' fuelling stations		Liquid H2 tank [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	Transformer & Rectifier	Deioniser	Electric Control	Electrolyser	Purifier	Compress or 30-400 bars	Intermediate storage 400 bars	Compressor 400-850 bars	Cryogenic pump [euros]	Hign pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.95	0.9	0.85	0.85	0.95	0.9	0.95	0.9	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0																				
2011	0																				
2012	0		210000	90000	70000	70000	307000	51000	256000	980000	123000	118000	145000	59000	110000	6000	40000	15000	70000	50000	2'770'000
2013	297		143621.00	26082.39	33940.19	20286.30	209960.22	24727.86	92846.75	355428.95	84120.87	57213.47	99166.88	28606.74	31878.48	2909.16	27356.38	10258.64	33940.19	14490.22	1'296'835
2014	654		137864.49	24271.40	31689.21	18877.75	201544.76	23087.85	85820.92	328533.19	80749.20	53418.95	95192.15	26709.48	29665.04	2716.22	26259.90	9847.46	31689.21	13484.11	1'221'421
2015	885		135742.20	23689.41	30894.19	18425.10	198442.17	22508.62	83450.26	319458.01	79506.15	52078.78	93726.76	26039.39	28953.73	2648.07	25855.66	9695.87	30894.19	13160.79	1'195'169
2016	1464		132313.73	22838.08	29649.47	17762.95	193430.07	21601.75	79859.17	305710.89	77498.04	49980.53	91359.48	24990.26	27913.21	2541.38	25202.61	9450.98	29649.47	12687.82	1'154'440
2017	1565		131870.10	22735.54	29491.97	17683.20	192781.53	21487.01	79415.51	304012.49	77238.20	49715.04	91053.16	24857.52	27787.88	2527.88	25118.11	9419.29	29491.97	12630.86	1'149'317
2018	1595		131742.13	22706.28	29446.70	17660.44	192594.45	21454.02	79288.41	303525.94	77163.25	49638.72	90964.81	24819.36	27752.11	2524.00	25093.74	9410.15	29446.70	12614.60	1'147'846
2019	1815		130889.11	22514.74	29146.62	17511.46	191347.41	21235.39	78451.16	300320.84	76663.62	49132.87	90375.81	24566.43	27518.02	2498.28	24931.26	9349.22	29146.62	12508.19	1'138'107
2020	2791		128103.14	21930.69	28187.59	17057.21	187274.58	20536.67	75835.82	290309.00	75031.84	47516.22	88452.16	23758.11	26804.18	2416.08	24400.60	9150.22	28187.59	12183.72	1'107'135
2021	3738		126260.11	21577.58	27570.83	16782.56	184580.25	20087.32	74203.48	284060.18	73952.35	46476.55	87179.60	23238.27	26372.60	2363.21	24049.54	9018.58	27570.83	11987.54	1'087'331
2022	4888		124604.96	21281.76	27028.93	16552.48	182160.59	19692.51	72802.04	278695.31	72982.91	45563.06	86036.76	22781.53	26011.05	2316.77	23734.28	8900.35	27028.93	11823.20	1'069'997
2023	6225		123140.04	21036.00	26558.76	16361.33	180019.01	19349.95	71611.42	274137.46	72124.88	44770.48	85025.27	22385.24	25710.66	2276.47	23455.25	8795.72	26558.76	11686.66	1'055'003
2024	7654		121908.58	20840.58	26170.37	16209.34	178218.73	19066.99	70645.95	270441.51	71403.60	44115.77	84174.97	22057.89	25471.82	2243.17	23220.68	8707.76	26170.37	11578.10	1'042'646
2025	9427		120686.03	20656.30	25790.99	16066.01	176431.48	18790.58	69718.85	266892.46	70687.53	43476.24	83330.83	21738.12	25246.59	2210.66	22987.81	8620.43	25790.99	11475.72	1'030'598
2026	11178		119699.99	20514.51	25489.49	15955.73	174989.99	18570.91	68993.51	264115.79	70110.00	42968.00	82650.00	21484.00	25073.29	2184.81	22800.00	8550.00	25489.49	11396.95	1'021'036
2027	13009		118832.69	20394.67	25227.61	15862.52	173722.08	18380.12	68371.80	261735.80	69602.01	42526.54	82051.15	21263.27	24926.82	2162.37	22634.80	8488.05	25227.61	11330.37	1'012'740
2028	14901		118064.48	20292.24	24998.23	15782.85	172599.03	18213.00	67833.68	259675.81	69152.05	42139.88	81520.71	21069.94	24801.62	2142.71	22488.47	8433.18	24998.23	11273.47	1'005'480
2029	16753		117407.88	20207.39	24804.11	15716.86	171639.15	18071.57	67382.99	257950.51	68767.48	41812.64	81067.35	20906.32	24697.93	2126.07	22363.41	8386.28	24804.11	11226.33	999'338
2030	18628		116818.20	20133.28	24631.28	15659.22	170777.08	17945.65	66985.41	256428.53	68422.09	41521.30	80660.18	20760.65	24607.34	2111.25	22251.08	8344.16	24631.28	11185.15	993'873

Concept 3 – Low Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser														
	Number of 'standard' fuelling stations		Liquid H2 tank [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	Transformer & Rectifier	Deioniser	Electric Control	Electrolyser	Purifier	Compresso r 30-400 bars	Intermediate storage 400 bars	Compressor 400-850 bars	Cryogenic pump [euros]	Hign pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.95	0.9	0.85	0.85	0.95	0.9	0.95	0.9	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0																				
2011	0																				
2012	0		210000	90000	70000	70000	307000	51000	256000	980000	123000	118000	145000	59000	110000	6000	40000	15000	70000	50000	2'770'000
2013	0		210000.00	90000.00	70000.00	70000.00	307000.00	51000.00	256000.00	980000.00	########	118000.00	145000.00	59000.00	110000.00	6000.00	40000.00	15000.00	70000.00	50000.00	2'770'000
2014	0		210000.00	90000.00	70000.00	70000.00	307000.00	51000.00	256000.00	980000.00	########	118000.00	145000.00	59000.00	110000.00	6000.00	40000.00	15000.00	70000.00	50000.00	2'770'000
2015	0		210000.00	90000.00	70000.00	70000.00	307000.00	51000.00	256000.00	980000.00	########	118000.00	145000.00	59000.00	110000.00	6000.00	40000.00	15000.00	70000.00	50000.00	2'770'000
2016	409		141253.49	25294.61	32997.67	19673.59	206499.15	24041.16	89849.49	343955.09	82734.19	55624.65	97532.17	27812.32	30915.64	2828.37	26905.43	10089.54	32997.67	14052.56	1'265'057
2017	759		136808.91	23976.48	31291.44	18648.37	200001.60	22798.05	84627.42	323964.34	80130.93	52748.43	94463.30	26374.21	29304.58	2682.12	26058.84	9772.07	31291.44	13320.26	1'208'263
2018	820		136274.63	23831.34	31091.88	18535.48	199220.54	22652.65	84034.21	321693.45	79818.00	52412.02	94094.39	26206.01	29127.19	2665.02	25957.07	9733.90	31091.88	13239.63	1'201'679
2019	839		136108.19	23786.68	31029.95	18500.75	198977.21	22607.54	83850.89	320991.69	79720.51	52307.63	93979.47	26153.82	29072.61	2659.71	25925.37	9722.01	31029.95	13214.82	1'199'639
2020	1027		134713.39	23422.73	30515.54	18217.68	196938.14	22232.75	82342.10	315215.84	78903.56	51440.48	93016.39	25720.24	28627.78	2615.62	25659.69	9622.38	30515.54	13012.63	1'182'732
2021	1342		132894.95	22975.00	29857.04	17869.44	194279.77	21752.99	80447.65	307963.64	77838.47	50330.44	91760.80	25165.22	28080.55	2559.18	25313.32	9492.50	29857.04	12763.89	1'161'202
2022	1940		130450.25	22418.57	28993.41	17436.67	190705.83	21123.77	78027.14	298697.66	76406.57	48874.60	90072.79	24437.30	27400.47	2485.15	24847.67	9317.87	28993.41	12454.76	1'133'144
2023	2788		128108.64	21931.79	28189.45	17058.06	187282.64	20538.03	75840.81	290328.11	75035.06	47519.36	88455.97	23759.68	26805.52	2416.24	24401.65	9150.62	28189.45	12184.33	1'107'195
2024	3634		126437.12	21610.39	27629.46	16808.08	184839.03	20130.03	74356.94	284647.67	74056.03	46575.37	87301.82	23287.69	26412.70	2368.24	24083.26	9031.22	27629.46	12005.77	1'089'210
2025	4617		124953.56	21342.44	27142.12	16599.68	182670.21	19774.98	73092.20	279806.09	73187.09	45753.86	86277.46	22876.93	26085.21	2326.47	23800.68	8925.25	27142.12	11856.91	1'073'613
2026	5639		123735.14	21134.06	26748.69	16437.60	180889.00	19488.33	72089.52	275967.70	72473.44	45090.65	85436.17	22545.32	25830.52	2292.74	23568.60	8838.22	26748.69	11741.14	1'061'056
2027	6780		122628.75	20953.64	26396.74	16297.28	179271.55	19231.91	71206.67	272588.04	71825.41	44497.37	84672.23	22248.68	25610.01	2262.58	23357.86	8759.20	26396.74	11640.91	1'049'846
2028	7924		121703.57	20809.01	26106.32	16184.79	177919.03	19020.32	70488.32	269838.08	71283.52	44007.80	84033.42	22003.90	25433.24	2237.68	23181.63	8693.11	26106.32	11560.56	1'040'611
2029	9198		120828.80	20677.34	25834.97	16082.37	176640.19	18822.62	69825.52	267300.82	70771.15	43550.39	83429.41	21775.19	25272.30	2214.43	23015.01	8630.63	25834.97	11487.41	1'031'994
2030	10718		119941.69	20548.71	25563.02	15982.33	175343.33	18624.49	69169.47	264789.39	70251.56	43091.95	82816.88	21545.98	25115.09	2191.12	22846.04	8567.26	25563.02	11415.95	1'023'367

Scenario 2

Concept 1 – High Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser							
	Number of 'standard' fuelling stations		Liquid H2 tank (50%) [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	Liquid H2 tank (50%) [euros]	Cryogenic pump [euros]	High pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.95	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0													
2011	0													
2012	0		135000	90000	70000	70000	135000	110000	20000	40000	15000	70000	50000	805'000
2013	298		92322.56	26079.58	33936.92	20284.12	92322.56	31875.04	9696.26	27354.83	10258.06	33936.92	14488.65	392'556
2014	657		88602.58	24260.52	31674.71	18869.29	88602.58	29651.74	9049.92	26252.62	9844.73	31674.71	13478.07	371'961
2015	885		87262.84	23689.41	30894.19	18425.10	87262.84	28953.73	8826.91	25855.66	9695.87	30894.19	13160.79	364'922
2016	1464		85058.82	22838.08	29649.47	17762.95	85058.82	27913.21	8471.28	25202.61	9450.98	29649.47	12687.82	353'744
2017	1565		84773.64	22735.54	29491.97	17683.20	84773.64	27787.88	8426.28	25118.11	9419.29	29491.97	12630.86	352'332
2018	1595		84691.37	22706.28	29446.70	17660.44	84691.37	27752.11	8413.34	25093.74	9410.15	29446.70	12614.60	351'927
2019	1815		84143.00	22514.74	29146.62	17511.46	84143.00	27518.02	8327.60	24931.26	9349.22	29146.62	12508.19	349'240
2020	2725		82449.02	21960.75	28238.71	17080.58	82449.02	26840.92	8068.20	24429.34	9161.00	28238.71	12200.42	341'117
2021	3651		81262.14	21604.93	27619.73	16803.84	81262.14	26406.03	7891.35	24077.67	9029.13	27619.73	12002.74	335'579
2022	4773		80196.25	21306.86	27075.87	16572.00	80196.25	26041.71	7735.96	23761.85	8910.69	27075.87	11837.14	330'710
2023	6079		79252.86	21059.21	26604.01	16379.38	79252.86	25739.03	7601.14	23482.33	8805.87	26604.01	11699.56	326'480
2024	7475		78459.82	20862.30	26214.22	16226.23	78459.82	25498.37	7489.78	23247.35	8717.76	26214.22	11590.17	322'980
2025	8957		77775.66	20700.40	25883.00	16100.31	77775.66	25300.49	7395.14	23044.64	8641.74	25883.00	11500.22	320'000

Concept 1 – Low Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser							
	Number of 'standard' fuelling stations		Liquid H2 tank (50%) [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	Liquid H2 tank (50%) [euros]	Cryogenic pump [euros]	High pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.95	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0													
2011	0													
2012	0		135000	90000	70000	70000	135000	110000	20000	40000	15000	70000	50000	805'000
2013	0		135000.00	90000.00	70000.00	0.00	135000.00	110000.00	20000.00	40000.00	15000.00	70000.00	50000.00	735'000
2014	0		135000.00	90000.00	70000.00	0.00	135000.00	110000.00	20000.00	40000.00	15000.00	70000.00	50000.00	735'000
2015	0		135000.00	90000.00	70000.00	0.00	135000.00	110000.00	20000.00	40000.00	15000.00	70000.00	50000.00	735'000
2016	409		90805.82	25294.61	32997.67	19673.59	90805.82	30915.64	9427.91	26905.43	10089.54	32997.67	14052.56	383'966
2017	759		87948.59	23976.48	31291.44	18648.37	87948.59	29304.58	8940.41	26058.84	9772.07	31291.44	13320.26	368'501
2018	820		87605.12	23831.34	31091.88	18535.48	87605.12	29127.19	8883.39	25957.07	9733.90	31091.88	13239.63	366'702
2019	839		87498.12	23786.68	31029.95	18500.75	87498.12	29072.61	8865.70	25925.37	9722.01	31029.95	13214.82	366'144
2020	1003		86705.91	23464.19	30575.04	18249.92	86705.91	28678.45	8735.73	25690.64	9633.99	30575.04	13035.66	362'050
2021	1311		85534.87	23013.04	29914.17	17899.03	85534.87	28127.05	8546.91	25343.66	9503.87	29914.17	12785.02	356'117
2022	1895		83960.52	22452.35	29047.43	17462.94	83960.52	27441.77	8299.27	24877.19	9328.95	29047.43	12473.53	348'352
2023	2723		82452.56	21961.85	28240.58	17081.44	82452.56	26842.26	8068.74	24430.39	9161.40	28240.58	12201.03	341'133
2024	3549		81376.13	21638.00	27678.56	16829.55	81376.13	26446.44	7908.16	24111.45	9041.79	27678.56	12021.11	336'106
2025	4387		80529.48	21397.92	27244.68	16642.83	80529.48	26153.02	7784.19	23860.59	8947.72	27244.68	11887.74	332'222

Concept 2 – High Uptake

	Number of 'standard' fuelling stations		Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser											
			Liquid H2 tank [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	SMR & PSA	Electric control unit	Compressor 15-400 bars	Intermediate storage 400 bars	Compressor 400-850 bars	Cryogenic pump [euros]	Hign pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.9	0.85	0.9	0.95	0.9	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0																	
2011	0																	
2012	0		210000	90000	70000	70000	1852000	500000	125000	145000	59000	110000	6000	40000	15000	70000	50000	3'412'000
2013	298		143612.87	26079.58	33936.92	20284.12	897873.91	181320.69	60601.64	99161.27	28603.97	31875.04	2908.88	27354.83	10258.06	33936.92	14488.65	1'612'297
2014	657		137826.24	24260.52	31674.71	18869.29	838022.44	167533.53	56561.99	95165.74	26697.26	29651.74	2714.98	26252.62	9844.73	31674.71	13478.07	1'510'229
2015	885		135742.20	23689.41	30894.19	18425.10	817372.00	162988.78	55168.20	93726.76	26039.39	28953.73	2648.07	25855.66	9695.87	30894.19	13160.79	1'475'254
2016	1464		132313.73	22838.08	29649.47	17762.95	784440.13	155974.95	52945.47	91359.48	24990.26	27913.21	2541.38	25202.61	9450.98	29649.47	12687.82	1'419'720
2017	1565		131870.10	22735.54	29491.97	17683.20	780273.38	155108.41	52664.24	91053.16	24857.52	27787.88	2527.88	25118.11	9419.29	29491.97	12630.86	1'412'714
2018	1595		131742.13	22706.28	29446.70	17660.44	779075.48	154860.17	52583.39	90964.81	24819.36	27752.11	2524.00	25093.74	9410.15	29446.70	12614.60	1'410'700
2019	1815		130889.11	22514.74	29146.62	17511.46	771136.19	153224.92	52047.53	90375.81	24566.43	27518.02	2498.28	24931.26	9349.22	29146.62	12508.19	1'397'364
2020	2725		128254.02	21960.75	28238.71	17080.58	747115.46	148384.51	50426.26	88556.35	23801.19	26840.92	2420.46	24429.34	9161.00	28238.71	12200.42	1'357'109
2021	3651		126407.77	21604.93	27619.73	16803.84	730739.06	145178.60	49320.94	87281.55	23279.48	26406.03	2367.41	24077.67	9029.13	27619.73	12002.74	1'329'739
2022	4773		124749.72	21306.86	27075.87	16572.00	716350.28	142426.19	48349.78	86136.71	22821.09	26041.71	2320.79	23761.85	8910.69	27075.87	11837.14	1'305'737
2023	6079		123282.23	21059.21	26604.01	16379.38	703866.02	140087.82	47507.16	85123.45	22423.38	25739.03	2280.34	23482.33	8805.87	26604.01	11699.56	1'284'944
2024	7475		122048.61	20862.30	26214.22	16226.23	693553.42	138191.65	46811.11	84271.66	22094.84	25498.37	2246.93	23247.35	8717.76	26214.22	11590.17	1'267'789
2025	8957		120984.37	20700.40	25883.00	16100.31	684790.26	136605.93	46219.65	83536.83	21815.67	25300.49	2218.54	23044.64	8641.74	25883.00	11500.22	1'253'225

Concept 2 – Low Uptake

	Number of 'standard' fuelling stations		Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser											
			Liquid H2 tank [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	SMR & PSA	Electric control unit	Compressor 15-400 bars	Intermediate storage 400 bars	Compressor 400-850 bars	Cryogenic pump [euros]	Hign pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.9	0.85	0.9	0.95	0.9	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0																	
2011	0																	
2012	0		210000	90000	70000	70000	1852000	500000	125000	145000	59000	110000	6000	40000	15000	70000	50000	3'412'000
2013	0		210000.00	90000.00	70000.00	70000.00	########	500000.00	125000.00	145000.00	59000.00	110000.00	6000.00	40000.00	15000.00	70000.00	50000.00	3'412'000
2014	0		210000.00	90000.00	70000.00	70000.00	########	500000.00	125000.00	145000.00	59000.00	110000.00	6000.00	40000.00	15000.00	70000.00	50000.00	3'412'000
2015	0		210000.00	90000.00	70000.00	70000.00	########	500000.00	125000.00	145000.00	59000.00	110000.00	6000.00	40000.00	15000.00	70000.00	50000.00	3'412'000
2016	409		141253.49	25294.61	32997.67	19673.59	873024.14	175487.29	58924.42	97532.17	27812.32	30915.64	2828.37	26905.43	10089.54	32997.67	14052.56	1'569'789
2017	759		136808.91	23976.48	31291.44	18648.37	827882.08	165287.93	55877.57	94463.30	26374.21	29304.58	2682.12	26058.84	9772.07	31291.44	13320.26	1'493'040
2018	820		136274.63	23831.34	31091.88	18535.48	822602.26	164129.31	55521.21	94094.39	26206.01	29127.19	2665.02	25957.07	9733.90	31091.88	13239.63	1'484'101
2019	839		136108.19	23786.68	31029.95	18500.75	820963.89	163771.27	55410.63	93979.47	26153.82	29072.61	2659.71	25925.37	9722.01	31029.95	13214.82	1'481'329
2020	1003		134875.86	23464.19	30575.04	18249.92	808928.32	161162.77	54598.29	93128.57	25770.39	28678.45	2620.72	25690.64	9633.99	30575.04	13035.66	1'460'988
2021	1311		133054.24	23013.04	29914.17	17899.03	791443.59	157442.09	53418.17	91870.78	25213.38	28127.05	2564.07	25343.66	9503.87	29914.17	12785.02	1'431'506
2022	1895		130605.25	22452.35	29047.43	17462.94	768511.98	152688.25	51870.41	90179.81	24482.83	27441.77	2489.78	24877.19	9328.95	29047.43	12473.53	1'392'960
2023	2723		128259.54	21961.85	28240.58	17081.44	747164.97	148394.32	50429.60	88560.16	23802.77	26842.26	2420.62	24430.39	9161.40	28240.58	12201.03	1'357'191
2024	3549		126585.09	21638.00	27678.56	16829.55	732295.74	145480.01	49426.01	87403.99	23329.08	26446.44	2372.45	24111.45	9041.79	27678.56	12021.11	1'332'338
2025	4387		125268.09	21397.92	27244.68	16642.83	720816.38	143273.99	48651.21	86494.63	22963.37	26153.02	2335.26	23860.59	8947.72	27244.68	11887.74	1'313'182

Concept 3 – High Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser														
	Number of 'standard' fuelling stations		Liquid H2 tank [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	Transformer & Rectifier	Deioniser	Electric Control	Electrolyser	Purifier	Compressor 30-400 bars	Intermediate storage 400 bars	Compressor 400-850 bars	Cryogenic pump [euros]	Hign pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.95	0.9	0.85	0.85	0.95	0.9	0.95	0.9	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0																				
2011	0																				
2012	0		210000	90000	70000	70000	307000	51000	256000	980000	123000	118000	145000	59000	110000	6000	40000	15000	70000	50000	2'770'000
2013	298		143612.87	26079.58	33936.92	20284.12	209948.34	24725.47	92836.19	355388.55	84116.11	57207.95	99161.27	28603.97	31875.04	2908.88	27354.83	#######	33936.92	14488.65	1'296'724
2014	657		137826.24	24260.52	31674.71	18869.29	201488.84	23077.29	85777.17	328365.72	80726.80	53394.52	95165.74	26697.26	29651.74	2714.98	26252.62	9844.73	31674.71	13478.07	1'220'941
2015	885		135742.20	23689.41	30894.19	18425.10	198442.17	22508.62	83450.26	319458.01	79506.15	52078.78	93726.76	26039.39	28953.73	2648.07	25855.66	9695.87	30894.19	13160.79	1'195'169
2016	1464		132313.73	22838.08	29649.47	17762.95	193430.07	21601.75	79859.17	305710.89	77498.04	49980.53	91359.48	24990.26	27913.21	2541.38	25202.61	9450.98	29649.47	12687.82	1'154'440
2017	1565		131870.10	22735.54	29491.97	17683.20	192781.53	21487.01	79415.51	304012.49	77238.20	49715.04	91053.16	24857.52	27787.88	2527.88	25118.11	9419.29	29491.97	12630.86	1'149'317
2018	1595		131742.13	22706.28	29446.70	17660.44	192594.45	21454.02	79288.41	303525.94	77163.25	49638.72	90964.81	24819.36	27752.11	2524.00	25093.74	9410.15	29446.70	12614.60	1'147'846
2019	1815		130889.11	22514.74	29146.62	17511.46	191347.41	21235.39	78451.16	300320.84	76663.62	49132.87	90375.81	24566.43	27518.02	2498.28	24931.26	9349.22	29146.62	12508.19	1'138'107
2020	2725		128254.02	21960.75	28238.71	17080.58	187495.17	20573.91	75972.87	290833.63	75120.21	47602.39	88556.35	23801.19	26840.92	2420.46	24429.34	9161.00	28238.71	12200.42	1'108'781
2021	3651		126407.77	21604.93	27619.73	16803.84	184796.12	20122.94	74331.44	284550.06	74038.83	46558.97	87281.55	23279.48	26406.03	2367.41	24077.67	9029.13	27619.73	12002.74	1'088'898
2022	4773		124749.72	21306.86	27075.87	16572.00	182372.21	19726.71	72922.21	279155.34	73067.70	45642.19	86136.71	22821.09	26041.71	2320.79	23761.85	8910.69	27075.87	11837.14	1'071'497
2023	6079		123282.23	21059.21	26604.01	16379.38	180226.88	19382.92	71724.97	274572.14	72208.17	44846.75	85123.45	22423.38	25739.03	2280.34	23482.33	8805.87	26604.01	11699.56	1'056'445
2024	7475		122048.61	20862.30	26214.22	16226.23	178423.45	19098.93	70754.12	270855.63	71485.62	44189.69	84271.66	22094.84	25498.37	2246.93	23247.35	8717.76	26214.22	11590.17	1'044'040
2025	8957		120984.37	20700.40	25883.00	16100.31	176867.62	18857.62	69942.23	267747.62	70862.27	43631.35	83536.83	21815.67	25300.49	2218.54	23044.64	8641.74	25883.00	11500.22	1'033'518

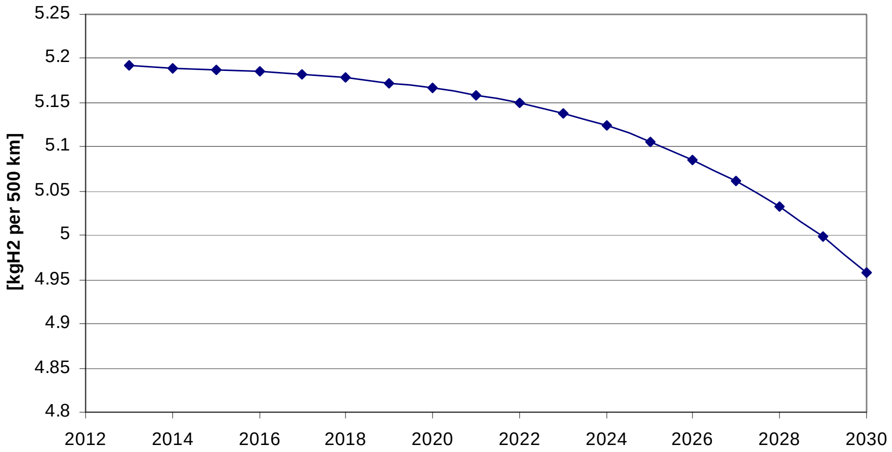
Concept 3 – Low Uptake

			Liquid hydrogen dispenser				Gaseous (700 bars) hydrogen dispenser														
	Number of 'standard' fuelling stations		Liquid H2 tank [euros]	Cryogenic pump [euros]	Dispenser [euros]	Other costs [euros]	Transformer & Rectifier	Deioniser	Electric Control	Electrolyser	Purifier	Compressor 30-400 bars	Intermediate storage 400 bars	Compressor 400-850 bars	Cryogenic pump [euros]	Hign pressure evaporator [euros]	High pressure buffer 300 bars [euros]	High pressure buffer 850 bars [euros]	Dispenser [euros]	Other costs [euros]	Total Unit Cost [euros per station]
		Progress Ratio	0.95	0.8	0.9	0.8	0.95	0.9	0.85	0.85	0.95	0.9	0.95	0.9	0.8	0.9	0.95	0.95	0.9	0.8	
2010	0																				
2011	0																				
2012	0		210000	90000	70000	70000	307000	51000	256000	980000	123000	118000	145000	59000	110000	6000	40000	15000	70000	50000	2'770'000
2013	0		210000.00	90000.00	70000.00	70000.00	307000.00	51000.00	256000.00	980000.00	123000.00	118000.00	145000.00	59000.00	########	6000.00	40000.00	15000.00	70000.00	50000.00	2'770'000
2014	0		210000.00	90000.00	70000.00	70000.00	307000.00	51000.00	256000.00	980000.00	123000.00	118000.00	145000.00	59000.00	########	6000.00	40000.00	15000.00	70000.00	50000.00	2'770'000
2015	0		210000.00	90000.00	70000.00	70000.00	307000.00	51000.00	256000.00	980000.00	123000.00	118000.00	145000.00	59000.00	########	6000.00	40000.00	15000.00	70000.00	50000.00	2'770'000
2016	409		141253.49	25294.61	32997.67	19673.59	206499.15	24041.16	89849.49	343955.09	82734.19	55624.65	97532.17	27812.32	30915.64	2828.37	26905.43	10089.54	32997.67	14052.56	1'265'057
2017	759		136808.91	23976.48	31291.44	18648.37	200001.60	22798.05	84627.42	323964.34	80130.93	52748.43	94463.30	26374.21	29304.58	2682.12	26058.84	9772.07	31291.44	13320.26	1'208'263
2018	820		136274.63	23831.34	31091.88	18535.48	199220.54	22652.65	84034.21	321693.45	79818.00	52412.02	94094.39	26206.01	29127.19	2665.02	25957.07	9733.90	31091.88	13239.63	1'201'679
2019	839		136108.19	23786.68	31029.95	18500.75	198977.21	22607.54	83850.89	320991.69	79720.51	52307.63	93979.47	26153.82	29072.61	2659.71	25925.37	9722.01	31029.95	13214.82	1'199'639
2020	1003		134875.86	23464.19	30575.04	18249.92	197175.66	22276.10	82515.34	315879.03	78998.72	51540.79	93128.57	25770.39	28678.45	2620.72	25690.64	9633.99	30575.04	13035.66	1'184'684
2021	1311		133054.24	23013.04	29914.17	17899.03	194512.63	21794.61	80610.35	308586.49	77931.77	50426.75	91870.78	25213.38	28127.05	2564.07	25343.66	9503.87	29914.17	12785.02	1'163'065
2022	1895		130605.25	22452.35	29047.43	17462.94	190932.43	21163.13	78176.38	299268.97	76497.36	48965.67	90179.81	24482.83	27441.77	2489.78	24877.19	9328.95	29047.43	12473.53	1'134'893
2023	2723		128259.54	21961.85	28240.58	17081.44	187503.24	20575.28	75977.89	290852.86	75123.45	47605.54	88560.16	23802.77	26842.26	2420.62	24430.39	9161.40	28240.58	12201.03	1'108'841
2024	3549		126585.09	21638.00	27678.56	16829.55	185055.35	20165.81	74485.76	285140.82	74142.70	46658.15	87403.99	23329.08	26446.44	2372.45	24111.45	9041.79	27678.56	12021.11	1'090'785
2025	4387		125268.09	21397.92	27244.68	16642.83	183130.01	19849.70	73356.28	280817.02	73371.31	45926.75	86494.63	22963.37	26153.02	2335.26	23860.59	8947.72	27244.68	11887.74	1'076'892

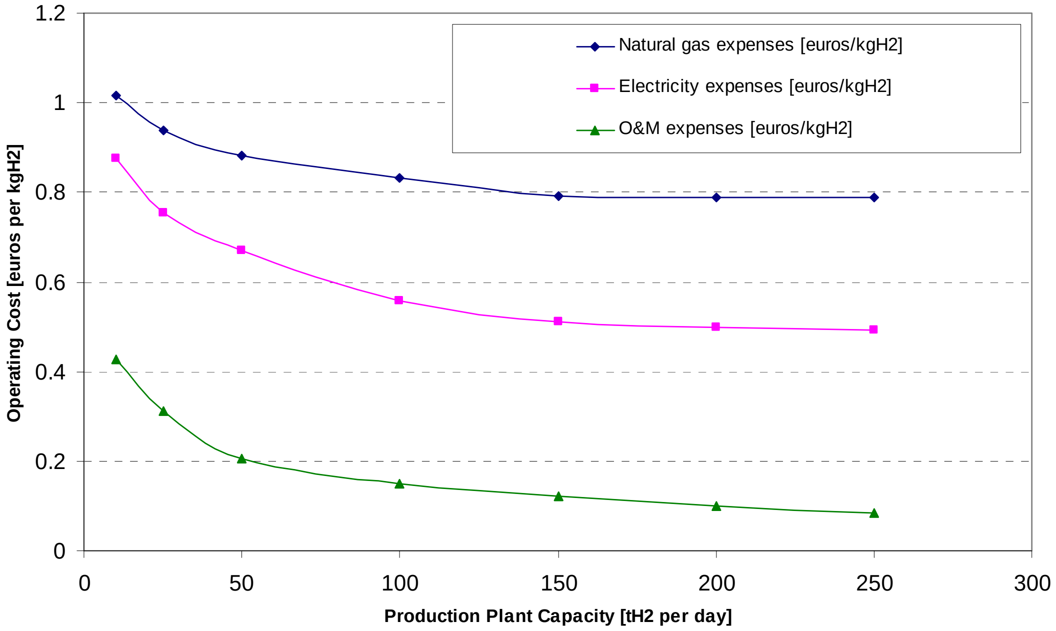
APPENDIX 4: Production and liquefaction plants initial investment cost [B. Valentin, 2001]

Capacity [tH2/day]	10	25	50	100	150	200	250
Production Plant (SMR & PSA) [million euros]	6.59	11.17	18.14	29.62	37.80	42.67	44.77
Liquefaction Plant [million euros]	27.58	45.53	68.14	103.40	132.57	158.38	181.95

APPENDIX 5: Evolution of the average fuel economy with the change of ICE and fuel cell based hydrogen vehicles share (*HyWays* hydrogen cars penetration rate, 10 years vehicle lifetime, 7 kgH2 per 500 km for ICE vehicles, 4 kgH2 per 500 km for fuel cell vehicles)



APPENDIX 6: Production and liquefaction plants specific operating cost in Germany [B. Valentin, 2001]



APPENDIX 7: Fuelling stations specific operating cost in Germany, inc. production of hydrogen for decentralised schemes [C. J. J. Reijerkerk, 2001]

	[euros per kgH2]
Concept 1 - electricity	0.057
Concept 2 - electricity	0.340
Concept 2 - gas	1.371
Concept 2 - water	0.054
Concept 3 - electricity	5.083
Concept 3 - water	0.054

APPENDIX 8: Operating fraction of the specific cost of hydrogen delivered at the pump in each country considered (production, liquefaction, transport distribution) – investment not included

Country	Concept 1 [euros per kg]	Concept 2 [euros per kg]	Concept 3 [euros per kg]
Austria	1.631	3.452	6.177
Belgium	1.504	3.101	4.847
Denmark	1.316	2.753	4.664
Finland	1.281	2.596	5.069
France	1.507	3.080	6.286
Germany	1.606	3.313	6.686
Greece	1.417	2.970	5.206
Ireland	1.604	3.520	5.090
Italy	1.937	4.358	5.972
Netherlands	1.354	2.741	5.555
Portugal	1.438	3.104	4.662
Spain	1.341	2.837	4.573
Sweden	1.304	2.365	7.281
United Kingdom	1.469	3.091	5.404
Switzerland	2.350	4.885	10.854
Hungary	1.371	2.959	4.308
Czech Republic	1.465	3.099	5.253
Poland	1.465	3.099	5.253

APPENDIX 9: Hydrogen selling price by country – based on a reference of 4 euros per kg in Germany (taxed gasoline equivalent), and on the ratio between gasoline price in Germany and gasoline price in other countries [Eurostat, 2003]

Austria	3.321
Belgium	3.826
Denmark	4.206
Finland	4.061
France	3.879
Germany	4.000
Greece	2.799
Ireland	3.244
Italy	4.028
Netherlands	4.457
Portugal	3.470
Spain	3.106
Sweden	3.858
United Kingdom	4.586
Norway	4.853
Switzerland	3.244
Hungary	3.721
Czech Republic	3.106
Poland	3.195

APPENDIX 10: Additional tables and figures

Table 1: Number of Hydrogen Vehicles – High and Low uptake

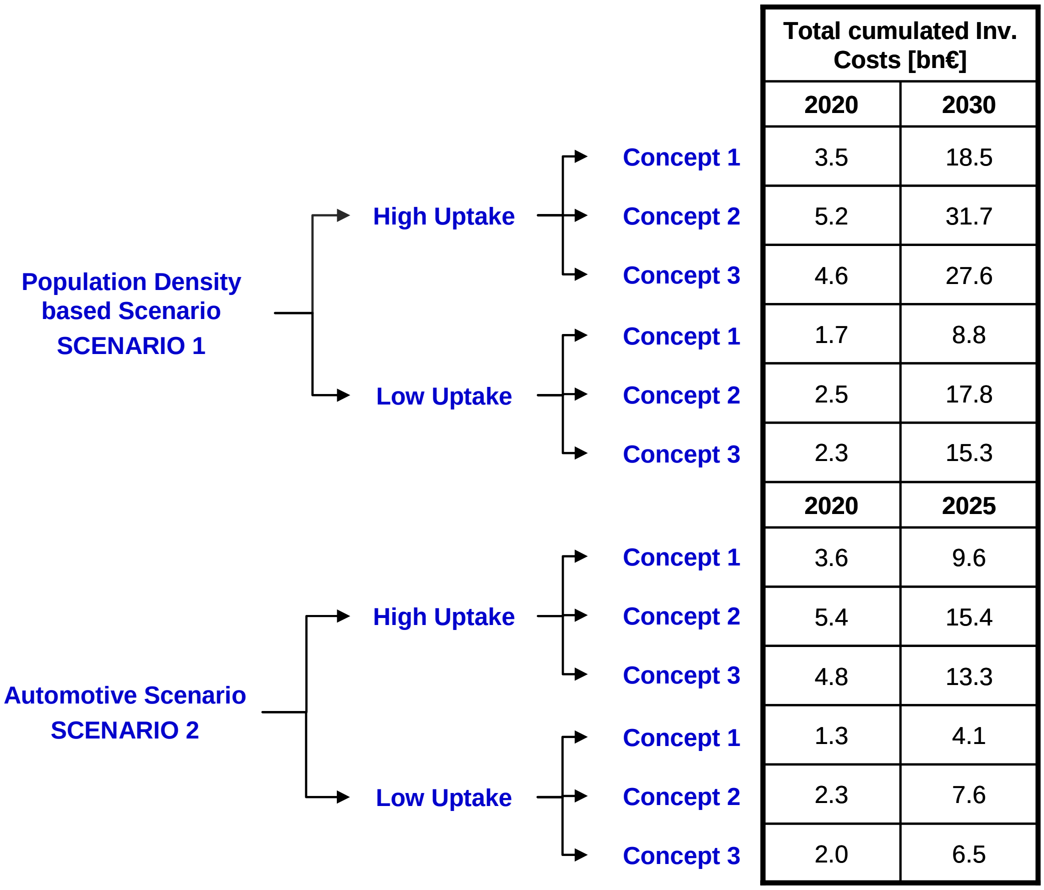
Year	**High uptake** **Number of hydrogen cars [millions]**	**Low uptake** **Number of hydrogen cars [millions]**
2010	0.00	0.00
2011	0.00	0.00
2012	0.00	0.00
2013	0.03	0.00
2014	0.28	0.00
2015	0.73	0.00
2016	1.20	0.02
2017	1.90	0.22
2018	2.86	0.58
2019	4.26	0.94
2020	6.09	1.30
2021	8.17	1.70
2022	10.70	2.47
2023	13.65	3.55
2024	16.84	4.63
2025	20.24	5.73
2026	24.10	7.02
2027	28.19	8.46
2028	32.47	9.92
2029	36.76	11.57
2030	41.20	13.54

Table 2: Fuelling Stations, Scenario 1 – Concept 1 - High uptake

Year	**N° of H_2 vehicles [million vehicles]**	**N° of fuelling stations**	**Total cost of fuelling stations [million euros]**	**Total cost of infrastructure [million euros]**
2015	0.7	885	222	453
2020	6.1	2,791	826	3,524
2030	41.2	18,628	6,002	18,512

Table 3: Production Plants, Scenario 1 – Concept 1 - High uptake

Year	N° of H_2 vehicles [million vehicles]	N° of production plants	Total cost of production plants [million euros]	Total cost of infrastructure [million euros]
2015	0.7	1	170	453
2020	6.1	19	2,305	3,524
2030	41.2	106	10,216	18,512



			Total cumulated Inv. Costs [bn€]	
			2020	**2030**
Population Density based Scenario SCENARIO 1	**High Uptake**	**Concept 1**	3.5	18.5
		Concept 2	5.2	31.7
		Concept 3	4.6	27.6
	Low Uptake	**Concept 1**	1.7	8.8
		Concept 2	2.5	17.8
		Concept 3	2.3	15.3
			2020	**2025**
Automotive Scenario SCENARIO 2	**High Uptake**	**Concept 1**	3.6	9.6
		Concept 2	5.4	15.4
		Concept 3	4.8	13.3
	Low Uptake	**Concept 1**	1.3	4.1
		Concept 2	2.3	7.6
		Concept 3	2.0	6.5

Figure 99: Pathways and total cumulated investment costs in billion euros

Table 4: Scenario 1, Concept 1, High Uptake – Population reached, H_2 vehicles served, investment costs and cost per H_2 car – by country

Country	Population reached [million]		H2 vehicles served [millions]		Investment cost [million euros]		Cost per hydrogen car [€ /hydrogen car]	
	2020	2030	2020	2030	2020	2030	2020	2030
Austria	0.08	1.4	0.04	0.7	132	362	3,329	516
Belgium	0.6	3.1	0.3	1.4	232	874	853	619
Denmark	0.0	0.8	0.0	0.3	0	159	0	577
Finland	0.0	0.5	0.0	0.2	0	145	0	665
France	2.2	12.6	1.1	6.1	570	2,797	538	456
Germany	3.5	21.6	1.9	11.6	870	4923	467	423
Greece	0.5	2.9	0.2	0.9	151	361	890	387
Ireland	0.0	0.4	0.0	0.2	0	130	0	827
Italy	1.1	8.3	0.6	4.7	355	1,953	549	412
Netherlands	0.5	2.8	0.2	1.2	174	539	782	466
Portugal	0.0	1.8	0.0	0.7	0	365	0	545
Spain	1.5	9.3	0.7	4.2	356	1,723	538	411
Sweden	0.0	0.7	0.0	0.3	0	174	0	517
UK	2.5	16.4	1.2	7.6	573	3,212	498	422
Switzerland	n/a	n/a	n/a	n/a	110	113	n/a	n/a
Hungary	0.0	1.1	0.0	0.3	0	179	0	645
Czech Republic	0.0	0.6	0.0	0.2	0	147	0	753
Poland	0.0	2.0	0.0	0.5	0	356	0	664

Table 5: Annual investment costs by Concept and stage in delivery chain – High Uptake Case

	Concept 1			Concept 2			Concept 3		
	Annual investment in Production Plants [million euros]	Annual investment in Trucks [million euros]	Annual investment in Fuelling Stations inc.on-site production [million euros]	Annual investment in Production Plants [million euros]	Annual investment in Trucks [million euros]	Annual investment in Fuelling Stations inc.on-site production [million euros]	Annual investment in Production Plants [million euros]	Annual investment in Trucks [million euros]	Annual investment in Fuelling Stations inc.on-site production [million euros]
2010	0	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	0	0
2013	0	4	54	0	3	223	0	3	179
2014	0	16	59	0	8	240	0	8	194
2015	170	41	109	0	30	440	0	30	357
2016	532	24	136	0	12	544	0	12	442
2017	372	41	27	665	17	107	665	17	87
2018	122	57	11	372	27	43	372	27	35
2019	349	81	55	122	43	222	122	43	181
2020	760	129	375	569	68	1492	569	68	1219
2021	422	123	265	0	65	1051	0	65	861
2022	709	146	317	647	77	1249	647	77	1025
2023	687	166	364	316	87	1433	316	87	1178
2024	576	175	385	412	93	1513	412	93	1246
2025	1'550	216	970	1168	114	3797	1168	114	3133
2026	891	210	555	572	111	2167	572	111	1790
2027	873	215	577	469	113	2248	469	113	1860
2028	857	222	590	462	116	2297	462	116	1902
2029	677	214	575	546	113	2233	546	113	1851
2030	669	214	578	626	113	2245	626	113	1862

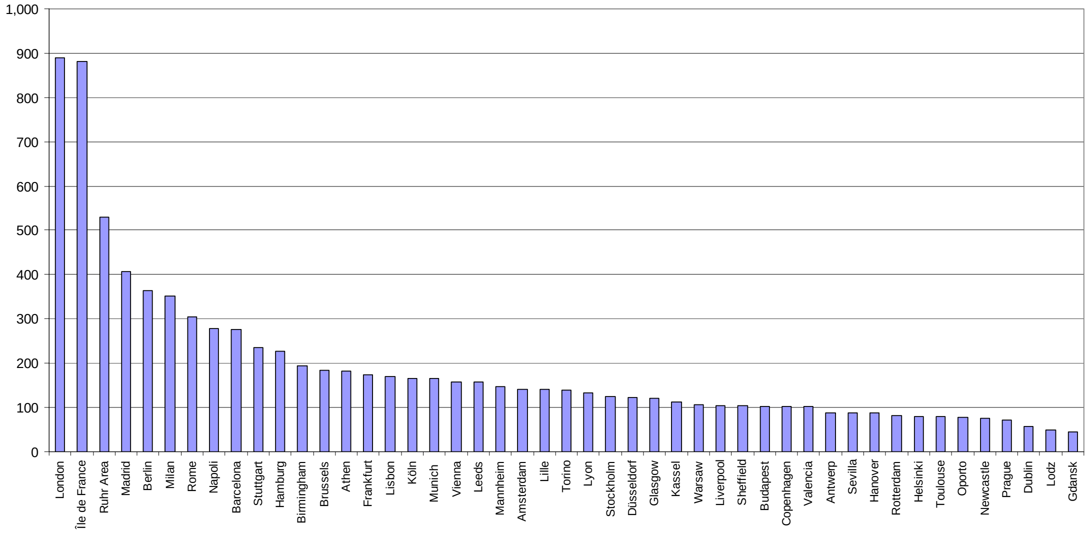


Figure 100: Fuelling stations by country, scenario 1, low uptake case

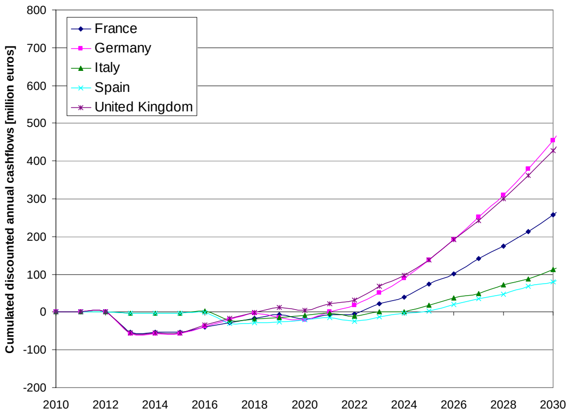


Figure 101: Break-even for one of two producers/transporters in selected EU countries, concept 1, low uptake, scenario 1

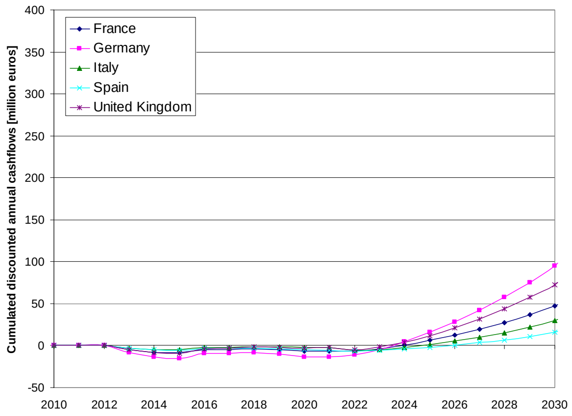


Figure 102: Break-even for one of three distributors in selected EU countries, concept 1, low uptake, scenario 1

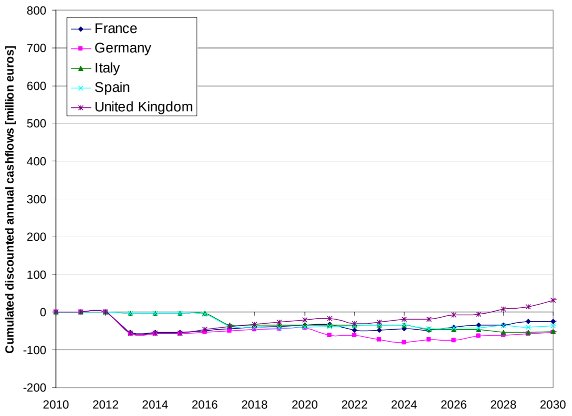


Figure 103: Break-even for one of two producers/transporters in selected EU countries, concept 2, low uptake, scenario 1

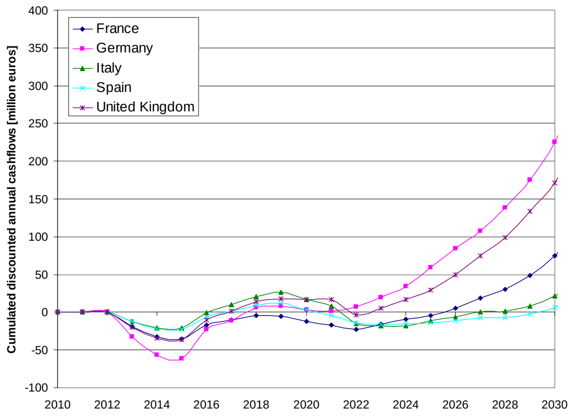


Figure 104: Break-even for one of three distributors in selected EU countries, concept 2, low uptake, scenario 1

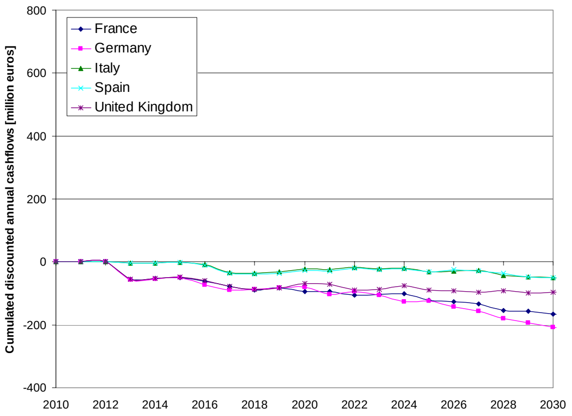


Figure 105: Break-even for one of two producers/transporters in selected EU countries, concept 3, low uptake, scenario 1

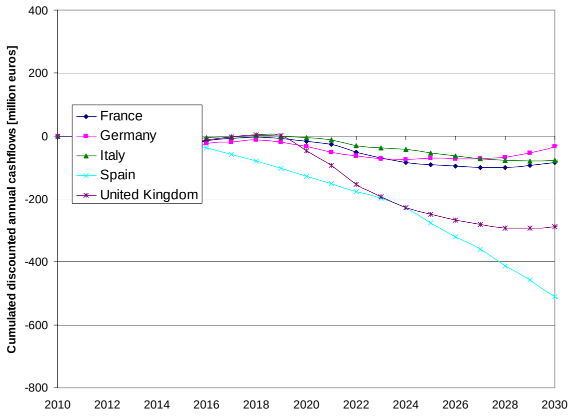


Figure 106: Break-even for one of three distributors in selected EU countries, concept 3, low uptake, scenario 1

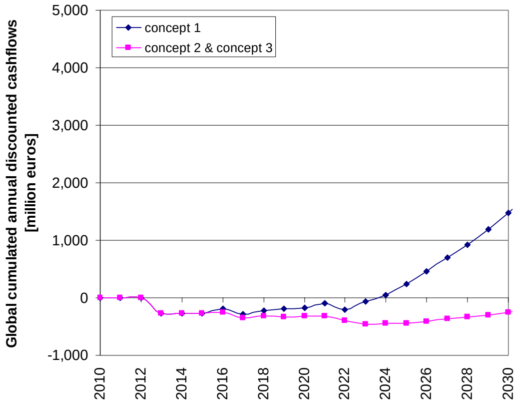


Figure 107: Break-even for one single producer/transporter in Europe, concept 1, 2 and 3, low uptake, scenario 1

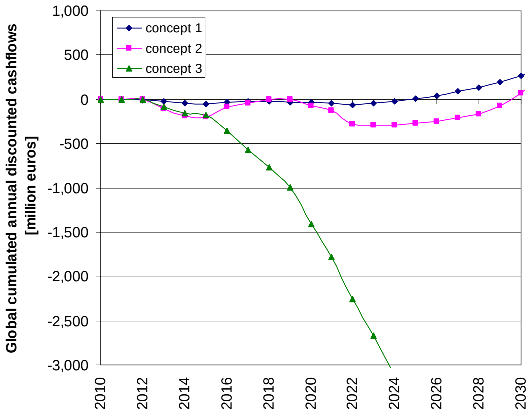


Figure 108: Break-even for one single distributor in Europe, concept 1, 2 and 3, low uptake, scenario 1

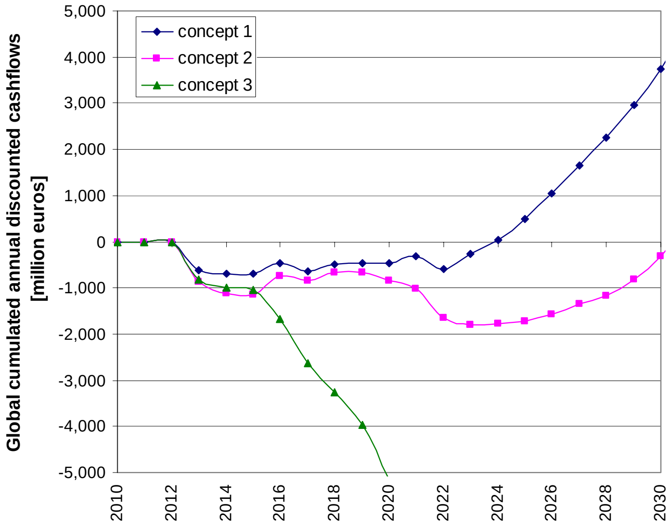


Figure 109: Break-even for one integrated supplier in Europe, concept 1, 2 and 3, low uptake, scenario 1

APPENDIX 11: Selected bibliography of hydrogen infrastructure studies

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APPENDIX 12: Selected infrastructure transitions

	Large upfront costs of infrastructure	Uncertain consumer response	Low added benefit to consumer	Requires consumer to have new appliance?	Involves delivery of an energy product? Is the product storeable?	Range of infrastructure scales used at once	Lumpiness of infrastructure/number of points of contact with user	Does the user move around? Are the routes fixed?	Ease of adding additional infrastructure at new demand point	Actors involved
Gasoline stations for cars	Yes. Probably not as large per station as hydrogen	No. Network of US stations only built after gasoline was clear winner. Networks described as coming in 1920s. In 1924, 3.2m gasoline cars were sold every year, versus 381 electric vehicles	Gradual build up of added benefits vs steam and electric	Yes	Yes - although liquid so easier to store	Yes - completely scaleable	Large	Yes. No fixed route	Easy - a tank and maybe a person to help refuel	Many small independent actors can be involved in the early days to support growing demand
Container ports	Yes, for first ports. The first ships did not need infrstructure as they had cranes on board	No - integrated company at first, then canvassed opinion in new areas	No	Yes - container ship	No	No - large ports only.	Very small - few ports	Yes, no fixed routes	Very difficult - whole new port. Though at first, ships had cranes on board	Same developers of ports and ships at first, then public and private investment in further ports?
The first electricity grid developments	Yes	No - electricity was a novelty paid for by those who could afford it, irrespective of the competition with gas	No - brighter and cleaner than gas light.	Yes	Yes - harder to store. Domestic use and transport - trams etc.	Yes - early mixture of small and large generation - small plants and large hydro/coal.	Very large - household level	No	Quite difficult - new generator, or extension of AC grid.	Electricity champions - Edison, von Siemens etc promoted and publicised DC. Uptake by wealthy few. Similarly Westinghouse championed AC. Spread to wider areas. Then combination of private owners (e.g. US, some UK), municipalities (Scandinavia, some UK), private owners for their own use - e.g. trams, factories (everywhere)
CNG cars in Argentina	Yes - but lower compared to hydrogen (e.g. if natural gas used no need for reforming and storage at refuelling station)	Yes	Cost benefit only	Yes	Yes - very similar	No - from pipelines already in place	Large	Yes. No fixed route	Yes. Quite easy - natural gas grid existed, need only new connection and equipment	Government-led and supported initially, in collaboration with the private sector, and through the state gas utility. Now privately run
Domestic gas networks	Initially small systems with large costs. Prospects of cheaper gas cost and established demand led to investment in large scale equipment and distribution network.	Certain market from wealthy customers and then low marginal cost for extending to other users	Net consumer benefit. Cheap compared to arc light. Not noisy, but smoky and hot. Relatively bright.	Yes	Yes - easier to store. Delivery to domestic level	Yes - early mixture of small gasifiers and large plants with pipes	Very large - household level	No	Quite difficult - new gasifier, or extension of pipeline.	Individuals and small actors for first systems, then entrepreneurs building large gasification plants and networks, selling to wealthiest people first

The following were also considered:

- Infrastructure for steam ships
- Canals in Europe
- EU mobile phone network
- Development of railways
- Transition from horses to steam on railways
- Transition from steam to diesel on railways
- Transition from diesel to electric on railways
- Broadband networks
- Long distance telephony
- The telephone in the US
- US rural electrification
- Town gas to natural gas transition
- Satellite/cable/digital terrestrial TV
- Gasoline stations in developing countries
- Green electricity sales
- Biofuels
- Motorways
- Cars in developing countries
- Electrification in developing countries
- Seatbelts, motorbike helmets
- FM radio