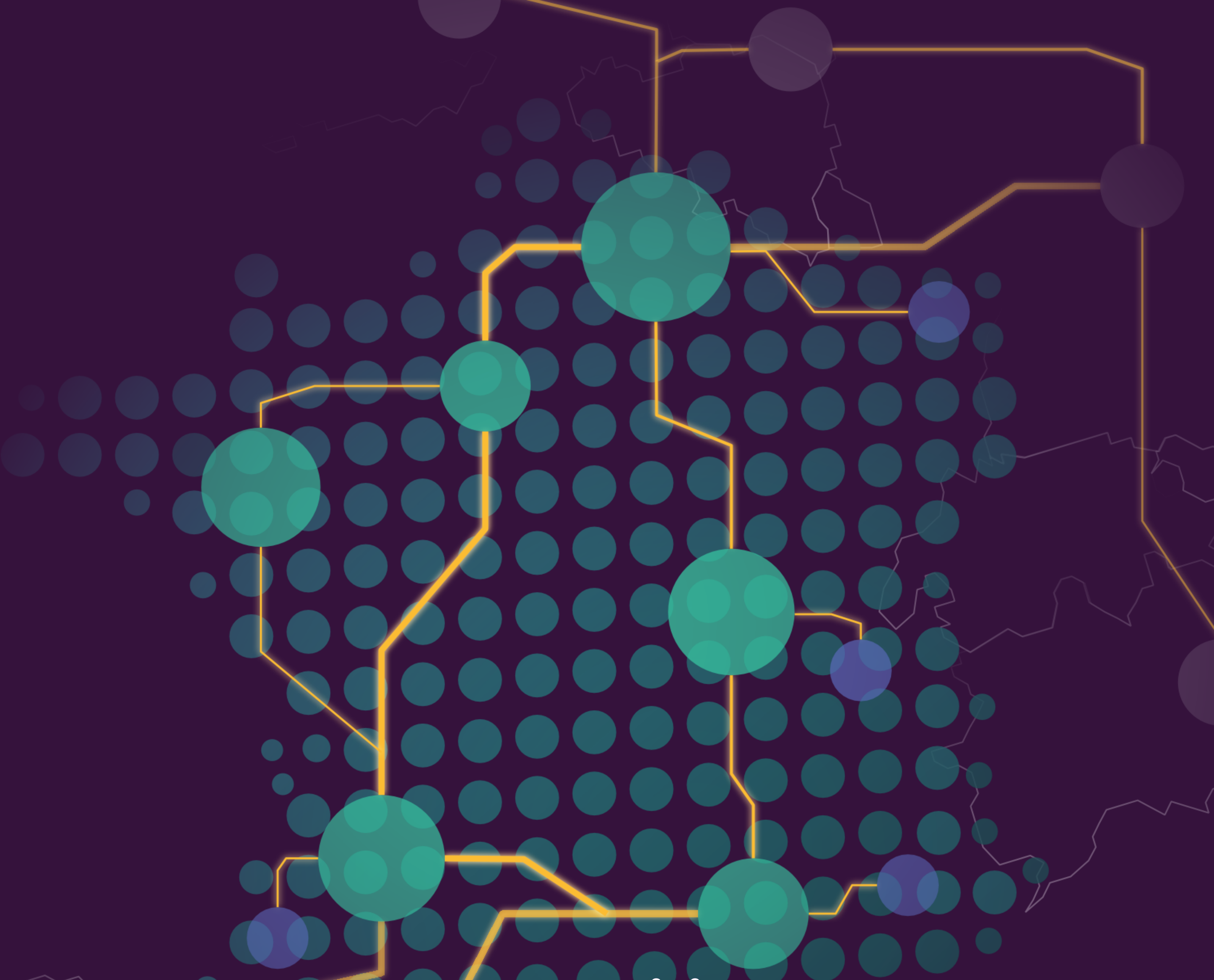

Competitiveness of France: Role of hydrogen transport and storage infrastructure

An initiative by GRTgaz, HDF Energy, Soladvent, Storengy, Teréga, TotalEnergies

Within the Comité Stratégique de Filière Nouveaux Systèmes Énergétiques (CSF NSE)

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An initiative by

Organised within the

The study is not binding on all CSF members.

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Executive summary

The role of hydrogen infrastructure in the context of achieving carbon neutrality in France

France is committed to achieving carbon neutrality by 2050, presenting challenges for all public, industrial, and financial actors. In this context, renewable and low-carbon hydrogen will play a major role alongside energy efficiency measures, low-carbon electricity, and other renewable gases. Hydrogen will be particularly essential in sectors that are difficult to decarbonise, such as industry (petrochemicals, fertiliser, steel), heavy-duty mobility, and dispatchable power generation.

To shed light on the role renewable and low-carbon hydrogen can play in decarbonising French industry while maximising its competitiveness, the companies GRTgaz, HDF Energy, Soladvent, Storengy, Teréga, and TotalEnergies, have studied – within the French Strategic Committee of the Industry (Comité Stratégique de Filière Nouveaux Systèmes Énergétiques, CSF NSE) – how transport and storage infrastructure can enable large-scale hydrogen deployment to meet targets set out in the French national hydrogen strategy. In its France 2030 plan, the government has reaffirmed its commitment to this strategy, which aims to reduce greenhouse gas emissions, develop a French hydrogen sector with electrolysers, fuel cells, refuelling stations, etc., and position France as a world leader in renewable and low-carbon hydrogen.

Through an integrated whole-system optimisation model of the French energy system (hydrogen and power) with hourly supply-demand balancing granularity, this study compares a range of infrastructure archetypes according to different performance indicators: the cost of hydrogen delivered, investment requirement, security of supply, and impact on competitiveness.

This simulation-based approach provides insights into the role of infrastructure within a dynamic market demand for renewable and low-carbon hydrogen. Several key messages emerge about the role of infrastructure, dependent on demand assumptions and subsequent modelling results.

An optimal deployment trajectory

The results of this study show the emergence of an optimal, progressive deployment trajectory for the development of dedicated hydrogen transport and storage infrastructure, starting within industrial clusters, stretching between industrial clusters, and eventually interconnecting with neighbouring countries. This deployment trajectory will be closely linked to the evolution of demand for renewable and low-carbon hydrogen. Considering the long deployment timelines for hydrogen pipelines and underground storage, optimisation of investment decisions will be greatly facilitated by developing a shared vision of the future infrastructure and the associated planning to get there, based on the model of 10-year network development planning currently in place for electricity and gas.

Benefits with regards to the cost of hydrogen delivered, investment needs, and industrial competitiveness

The modelling results indicate that the implementation of hydrogen transport and storage infrastructure between industrial clusters could allow a consolidation of hydrogen production capacities and a reduction in the cost of hydrogen delivered by 10% by 2030 (when annual hydrogen demand in France is estimated to be 670 kt). Moreover, the connection of French infrastructures to the rest of Europe could reduce the cost of hydrogen by 32% by 2040 (with French hydrogen demand estimated at 1800 kt/year), provided that the production and consumption strategies of neighbouring countries materialise.

Hydrogen infrastructure between industrial clusters would reduce cumulative investment costs by 9%, or €300 million, by 2030 and by 19%, or €3 billion, by 2040 compared to a scenario without hydrogen infrastructure.

By providing access to competitive hydrogen and by improving security of supply, these infrastructures could improve the competitiveness and attractiveness of French territories for industry. In addition, by pooling supply sources and utilising large-scale underground storage facilities, they can improve overall energy system resiliency and help to assert national energy sovereignty. Dedicated hydrogen storage facilities in particular can play a dual role by providing both short-term flexibility for firming renewable energy generation profiles and strategic reserves to absorb extended periods of low renewable energy production.

Finally, hydrogen infrastructure can contribute to the development of a competitive French electrolyser sector by creating clear market signals and long-term investment certainty for large-scale electrolysis production projects.

Defining France's strategy considering ongoing initiatives by our European neighbours

When defining France's hydrogen infrastructure strategy, it will be necessary to take into account various initiatives by other European countries, some of which are in the process of implementing national hydrogen strategies containing dedicated transport and storage infrastructure components. France is well-placed to be part of and benefit from a pan-European interconnected hydrogen network. It will be important to determine how France can leverage its strategic geographic location.

Further work to maximise benefits

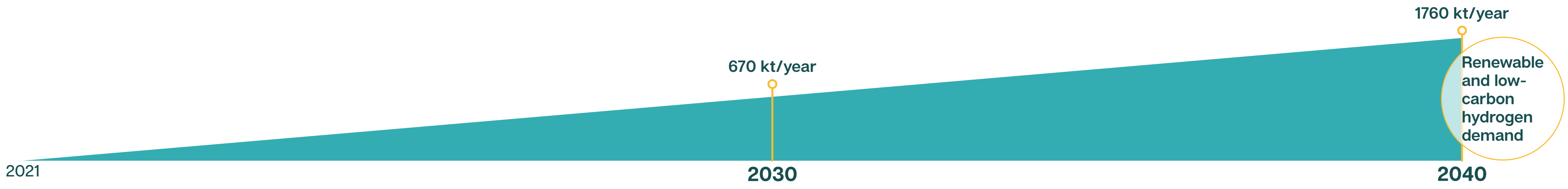
Following this initial study, seven optimisation levers have been identified to maximise the benefits of hydrogen infrastructure and optimise the total investment cost. These are:

1. Collaboration with power and gas transport companies to optimise investments in power, gas, and hydrogen infrastructure in an integrated manner;
2. Assessment of trade-offs between existing and new infrastructure to maximise repurposing potential and optimise costs;
3. Optimisation, scale-up, and integration of large-scale renewable energy capacities (offshore wind, onshore wind, solar PV) in conjunction with nuclear production;
4. Development of underground hydrogen storage for local and inter-regional use;
5. Definition of transition trajectories within industrial clusters, between industrial clusters, and with European interconnections for 2030, 2040, and 2050 – in step with market demand;
6. Utilisation of low-carbon hydrogen production by SMR CCS (conversion of existing SMR production units with CCS as well as new units);
7. Collaboration with neighbouring countries and the EU to identify transit needs and secure the associated investment requirements.

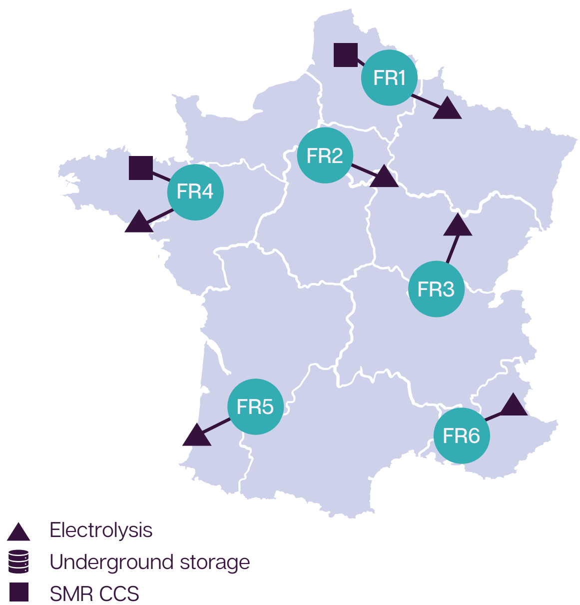
It is therefore proposed to continue working in collaboration with the government, particularly given the revision of the Multiannual Energy Programme ("Programmation Pluriannuelle de l'Énergie") and the National Low-Carbon Strategy ("Stratégie Nationale Bas-Carbone").

The French Strategic Committee of the Industry has thus planned to deepen the analysis by expanding the group of stakeholders to include players from the electricity industry – especially the transmission operator –, the main industrial consumers at the heart of the French industrial clusters, and electrolyser manufacturers that wish to contribute to the discussion.

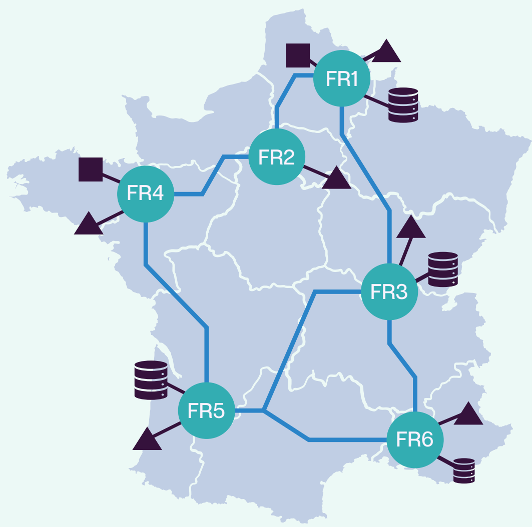
With the State reaffirming its ambitions on the competitiveness of low-carbon hydrogen and the acceleration of the implementation of the hydrogen strategy, the continuation of this work will contribute directly to these priorities. Refinement of the results of this study and subsequent dissemination with policy makers can complement the national hydrogen strategy and accelerate the implementation towards a decarbonised and competitive industry.



Isolated national ecosystems

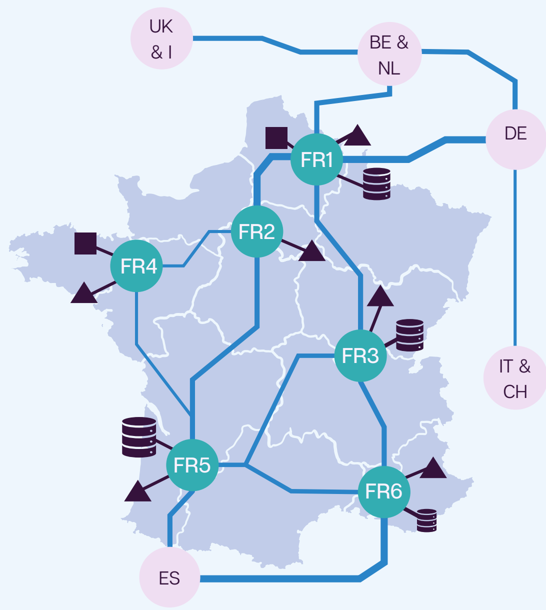


Integrated national ecosystems



- 10 % reduction in cost of H_2 delivered.
- 9 % reduction in investment cost.

Integrated national and European ecosystems



- 32% reduction in cost of H_2 delivered.
- €1,6 Bn investment cost.

A no-regret trajectory

- Development of hydrogen infrastructure within and between industrial clusters.
- Conversion of existing natural gas infrastructure.
- Strategic hydrogen infrastructure planning.

Additional benefits

Storage | Security of supply, system resiliency, national energy sovereignty.

Expansion of electrolyser production capacities.

Competitiveness of French industry.

Source: Results based on the modelling study conducted by Guidehouse with assumptions presented in the Appendix of the report.

1. Introduction and methodology

The objective of this study, conducted by Guidehouse, is to provide an assessment of the role of hydrogen transport and storage infrastructure in the context of the French hydrogen strategy and, more generally, in a European decarbonisation context.

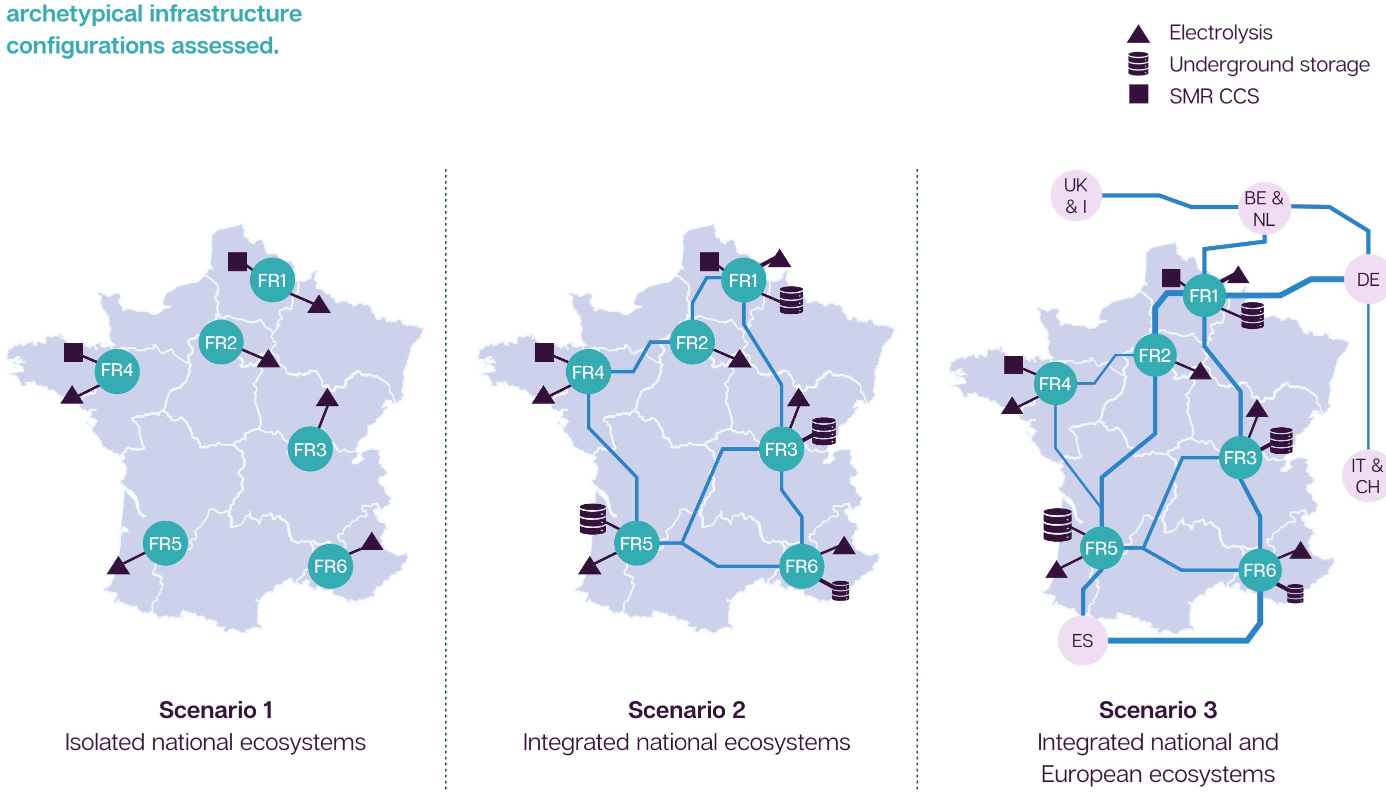
The methodology is based on a capacity expansion model of the French energy system that optimises (minimises) total energy system costs. The model considers an hourly balancing of supply and demand for representative days per season for the power and hydrogen system. The geographical scope of the model covered France and its neighbouring regions: Spain, Italy, Switzerland, Germany, Belgium, the Netherlands, and the United Kingdom. For more geographical granularity, France was divided into 6 representative regions.

Three archetypical infrastructure scenarios were modelled:

- **Scenario 1: Isolated national ecosystems |** Hydrogen production occurs only on-site without dedicated hydrogen transport and storage infrastructure.
- **Scenario 2: Integrated national ecosystems |** Hydrogen production occurs only at a national (French) level. Dedicated transport networks between industrial clusters are limited to the national territory without interconnections with neighbouring countries. A dedicated semi-centralised hydrogen storage infrastructure system exists.
- **Scenario 3: Integrated national and European ecosystems |** Hydrogen is produced nationally and imported from neighbouring countries. A dedicated transport network, including cross-border interconnections, is available to attain the most competitive utilisation of hydrogen, alongside the presence of a dedicated centralised hydrogen storage system.

FIGURE 1

Illustrative presentation of the three archetypical infrastructure configurations assessed.



Source: Guidehouse

The study analyses several configurations of the French energy system with different demand assumptions, production cost forecasts, and boundary conditions for electricity and hydrogen infrastructure. The conclusions presented in this report refer specifically to the base demand scenario, described in more detail below. The quantitative results are therefore specific to this base scenario, but a sensitivity analysis reveals that the general qualitative trends and conclusions regarding the value and role of hydrogen infrastructure are also relevant in the other scenarios. All demand, supply, and infrastructure assumptions adopted are presented in the table below.

TABLE 1

Summary of assumptions for the base demand scenario.

Demand	**Hydrogen |** the study is based on an estimated "base" hydrogen demand in France of 670 kt/year by 2030, or 22.1 TWh (lower calorific value[1]), mainly for use in industry, mobility and for dispatchable power generation. In the industrial sector, the estimate was based on bottom-up assessments of industrial hydrogen demand by site. In mobility, the assessment was done by region. The study only accounts for the additional demand for renewable and low-carbon hydrogen: the conversion of existing grey hydrogen is not included. This is consistent with the result communicated by France Hydrogène in the study: "A roadmap for an ambitious Hydrogen strategy"[2]. The assumptions adopted concerning hydrogen demand in other European countries are taken from the European Hydrogen Backbone (EHB) study.[3] Note: A high demand scenario of 1300 kt/year by 2030 has also been considered. This summary paper does not present the modelling results of this high demand scenario, which is only covered in the full study. **Electricity |** The assumptions regarding electricity demand in France are based on scenarios developed by RTE, France's power transmission system operator. For other European countries, demand assumptions are based on ENTSO-E's and ENTSOG's joint "Ten Year Network Development Plan" (TYNDP).
Supply	**Hydrogen |** Hydrogen production capacities are outputs obtained from the capacity expansion optimisation model. For electrolysis production, it is assumed that the electricity used comes from the power grid. For blue hydrogen, several constraints are set on the availability of carbon capture and storage (CCS) in different regions. The supply parameters used for hydrogen imports are based on national strategies and the EHB report. **Electricity |** RTE (N1 Nuclear scenario, 2020 version) and TYNDP assumptions are considered for the business-as-usual deployment scenario, with additional capacities added afterwards as per results of the capacity expansion optimisation model.
Infrastructure	**Hydrogen |** Capacities, timing, and potential for conversion of existing natural gas pipelines are based on data provided by transport companies GRTgaz and Teréga. Storage volume potentials, capacity potentials, and locations are based on data from storage operators Storengy and Teréga. **Electricity |** TYNDP and RTE assumptions and scenarios (2020 version) are used.

1 In this study, the energetic value of hydrogen is expressed using its lower calorific value (1 kt = 33.3 GWh).

2 France Hydrogène (2021): Trajectory for a great hydrogen ambition. https://www.afhypac.org/presse/sur-la-trajectoire-d-une-grande-ambition-hydrogene-3405/

3 European Hydrogen Backbone (2021): Analysing future demand, supply, and transport of hydrogen. https://gasforclimate2050.eu/sdm-_downloads/2021-ehb-analysing-future-demand-supply-and-transport-of-hydrogen/

2.

The role of transport and storage infrastructure in reducing the cost of hydrogen delivered and the investments required

Key messages

Cost of hydrogen delivered

- The implementation of hydrogen infrastructure between French industrial clusters can reduce the cost of hydrogen delivered by 10% by 2030 (estimated hydrogen demand of 670 kt/year) and by 4% by 2040 (estimated hydrogen demand of 1800 kt/year);
- Connecting French hydrogen infrastructure to the rest of Europe will reduce the cost of hydrogen by 19% by 2030 (670 kt/year) and by 32% by 2040 (1800 kt /year).

Cumulative investment costs

- Hydrogen infrastructure connecting French industrial clusters could reduce cumulative investment costs by 9% in 2030 (670 kt/year) and 19% by 2040 (1800 kt/year);
- Delivering dedicated infrastructure needed to create and maintain a liquid inter connected hydrogen market would require additional investment costs of around €3.9 billion by 2030 (670 kt/year) and €1.6 billion by 2040 (1800 kt/year).

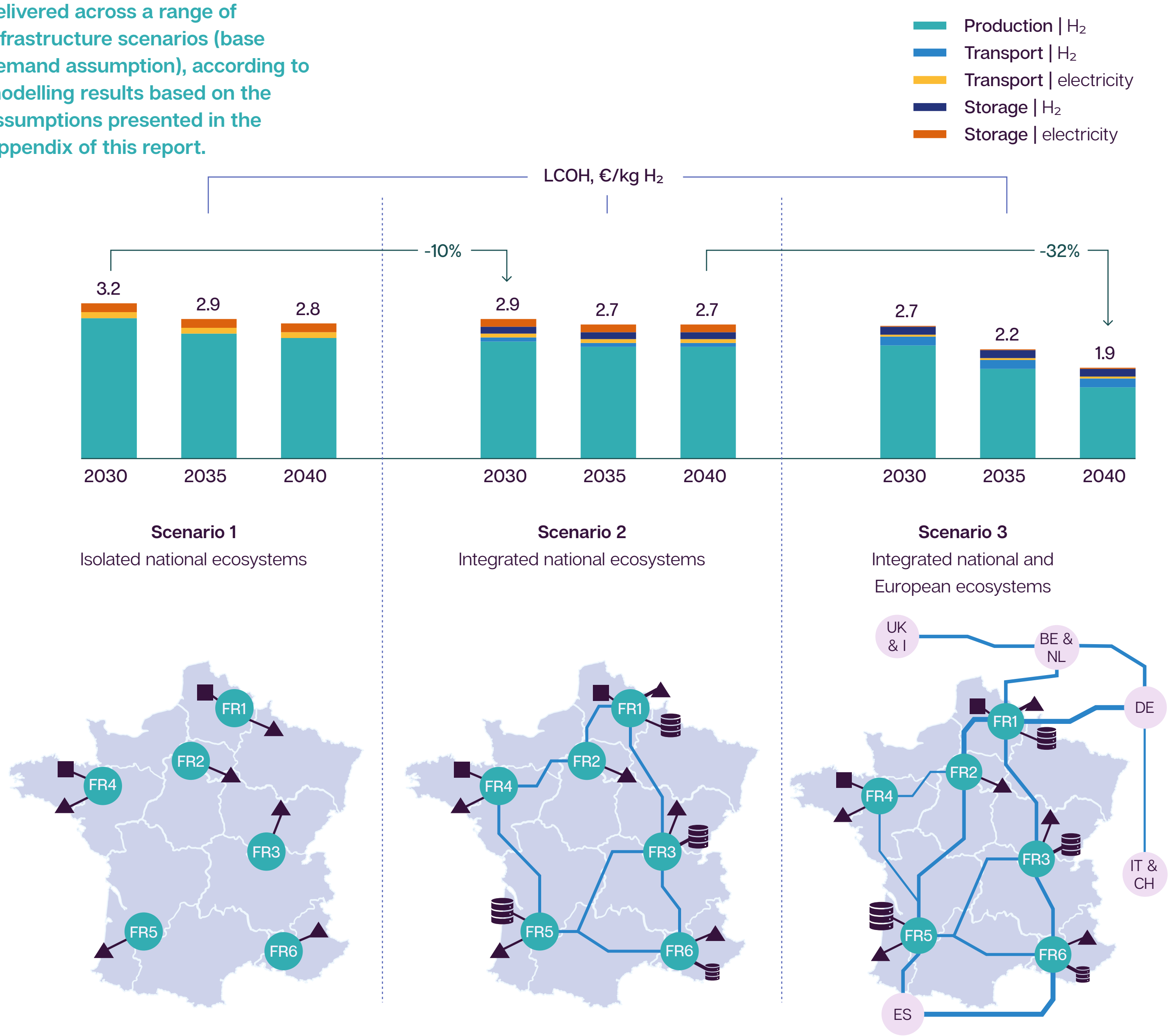
Based on the modelling methodology described above, this study assesses two key economic indicators of critical importance to hydrogen market players, policy makers and regulators for a range of infrastructure configurations.

2.1 Impact of hydrogen infrastructure on the cost of hydrogen delivered

First, the study estimates the levelised cost of hydrogen (LCOH) delivered, illustrated in Figure 2. This reflects the unit cost per kilogram of hydrogen paid by a customer connected to the transmission system, and covers production, transport (excluding distribution), and storage. This parameter is essential for any industrial or other hydrogen consumer, as it represents a major variable cost and therefore strongly influences its competitiveness in the market.

FIGURE 2

Levelised cost of hydrogen (LCOH) delivered across a range of infrastructure scenarios (base demand assumption), according to modelling results based on the assumptions presented in the Appendix of this report.



Source: Guidehouse

For example, if a steel producer like ArcelorMittal wishes to produce 1.6 million tons of Direct Reduced Iron (DRI) from green hydrogen per year[4], it would need about 4.2 TWh or 130 kt of hydrogen per year[5]. In this case, a hypothetical difference in the cost of hydrogen delivered of €0.5 per kg hydrogen translates into an increase in annual operating costs of €64 million.

The results in Figure 2 show that the development of transport and storage infrastructure can reduce the cost of hydrogen by enabling economies of scale and by increasing the utilisation factor of production assets. Dedicated hydrogen transport and storage infrastructure between industrial clusters (S2) has the potential to reduce the cost of renewable and low-carbon hydrogen for French consumers, including industry, by 10% by 2030 (hydrogen demand estimated at 670 kt/year), representing cost savings of €0.3/kg (from €3.2 to €2.9), compared to a scenario where no dedicated hydrogen infrastructure is present (S1). This differential represents a cost reduction of €200 million per year when considering the total French demand.

4 As the company plans to do in Gijon, Spain. https://corporate.arcelormittal.com/media/press-releases/arcelormittal-signs-mou-with-the-spanish-government-supporting-1-billion-investment-in-decarbonisation-technologies.

5 Assuming that 2.6 MWh of hydrogen is needed to produce 1 ton of steel. https://ssabwebsitecdn.azureedge.net/-/media/hybrit/files/hybrit_brochure.pdf.

Moreover, dedicated hydrogen infrastructure connecting France to the rest of Europe (S3) would reduce the cost of hydrogen for French consumers by 32% by 2040 (hydrogen demand estimated at 1800 kt/year), representing cost savings of 0.9 €/kg compared to a scenario where no dedicated hydrogen infrastructure is present. By 2040, the difference in hydrogen cost of €0.9/kg between S3 and S1 represents a reduction of €1.7 billion per year when considering the total French demand, or about €17 billion between 2030 and 2040.

"

ArcelorMittal, the world's leading steel company, has committed to reducing its CO_2 emissions by 25% globally and 35% in Europe in 2030 compared to 2018, and to achieving carbon neutrality globally by 2050. To achieve this, we need to carry out a real industrial revolution, where hydrogen will have a crucial place, as a substitute for coal, in new iron ore processing facilities, DRIs. For example, the project we are developing at the Dunkirk site aims to implement a hydrogen-powered DRI with a capacity of 2 million metric tons, emitting three times less CO_2 than a blast furnace.

Hydrogen could also be used to recover the residual CO_2 emitted by transforming it into fuel or into an input for other industries. Considerable quantities of hydrogen will be needed, several hundred kt/year in the long term, which will have to be supplied to us in a secure and stable way, at a competitive cost. This is why the development of domestic supply infrastructures and international interconnections is absolutely vital to achieve this. The development of these hydrogen production and distribution networks could also contribute to the decarbonisation of other industrial and mobility players, thus forming the basis for a low-carbon economy in France.

Eric NIEDZIELA Macron, President of ArcelorMittal France, and Vice President Climate Action ArcelorMittal Europe.

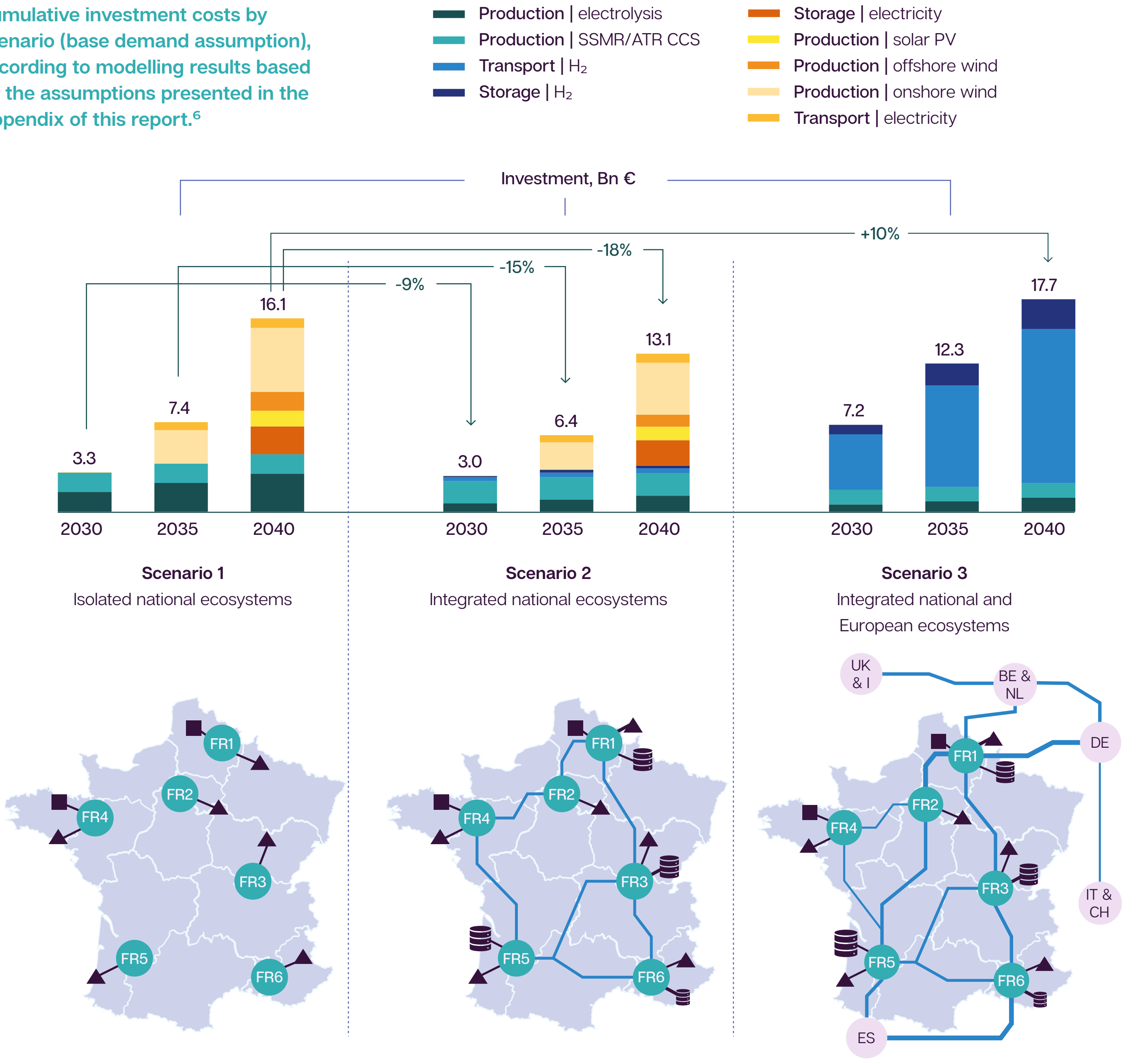
2.2

Impact of hydrogen infrastructure on investment costs

Secondly, the study calculates and presents the total (incremental) investment cost, as shown in Figure 3, reflecting the capital investment required across all parts of the energy system – generation, transmission and storage, for both hydrogen and electricity – in addition to the base infrastructure deployment scenario assumed in the model (RTE scenario N1).

FIGURE 3

Cumulative investment costs by scenario (base demand assumption), according to modelling results based on the assumptions presented in the Appendix of this report.[6]



Source: Guidehouse

The results in Figure 3 demonstrate that the additional investment costs across electricity and hydrogen production, transport and storage infrastructure in France would be 9% lower by 2030 and 15% lower by 2035, or about €0.3 billion and €1.0 billion, in a scenario where French hydrogen production and storage locations and clusters are connected to each other (S2) compared to a scenario where no dedicated hydrogen infrastructure is present (S1).

6 Note that this analysis takes into account the scaling effect of cell size between the different scenarios. The CAPEX of electrolysers in S1 has been increased by 25%, a rather conservative assumption (according to an IRENA study the difference between 10 MW and 50 MW electrolysers is 50%). Furthermore, the estimated cost does not take into account the storage of H_2 and electricity potentially needed on site. This is a conservative assumption that underestimates the cost of hydrogen in S1.

The cumulative investments needed in S2 are lower than the amounts needed in S1 for the entire modelled period from 2030 to 2040. This is because a scenario without hydrogen infrastructure (S1) requires additional investments to be made in electricity infrastructure from 2030 onwards, first to enhance production needs, and subsequently also to reinforce electricity storage required for dispatchable power generation.

By 2040, the investments required to develop an interconnected hydrogen network linked to the rest of Europe (S3) are higher, by €1.6 billion compared to S1 and by €4.6 billion compared to S2. This is reflective of increased investment in hydrogen transport and storage infrastructure. However, the benefits of these investments are passed on to the French economy through more attractive hydrogen prices for consumers, an anticipated increase in jobs in French industry due to a thriving liquid hydrogen market, and accelerated decarbonisation of the mobility and industrial sectors. These investments also represent long-term market signals that provide certainty to consumers and in particular to industry.

The benefits related to market liquidity and accelerated decarbonisation are, to a lesser extent, also valid for the national infrastructure configuration (S2), which requires less investment. This highlights the no-regret trajectory, which starts with S2 and moves towards S3 as the market matures.

2.3 Senitivity analysis

To ensure the robustness of the modelled results, several sensitivity analyses were conducted as part of the study, as well as additional modelling with a second set of assumptions.

The main sensitivities modelled were:

- High demand assumption of 1,300 kt/year in 2030 (results in Appendix);
- 100% increase in capital costs (CAPEX) for electrolysers;
- 50% reduction in capital costs (CAPEX) of SMR/ATR + CCS (blue hydrogen production);
- 50% increase in hydrogen import costs from Spain;
- Changes in financial parameters such as cost of capital (WACC) and amortization period.

The overall conclusions regarding the value and benefits of hydrogen infrastructure remain the same: the cost of hydrogen delivered is reduced and a no-regret implementation trajectory emerges.

3. The impact of infrastructure on industrial competitiveness and attractiveness, system resiliency, and the French electrolyser sector

Key messages

Competitiveness and attractiveness of territories

- The decisions taken now are crucial to maintain, develop, and attract industrial players in France who require more certainty on future prices and availability of renewable and low-carbon hydrogen in their territory, to justify making investment decisions today;
- Infrastructure, whether energy, telecom or other, is a basic condition for deciding to set up or maintain certain industries in a particular area. Easy access to renewable and low-carbon energy at a competitive cost is therefore an asset for industrial actors;
- Hydrogen infrastructure represents a considerable advantage for local production projects by guaranteeing a physical off-take and by enabling scale economies to be achieved.

Resilience, security of supply and energy sovereignty

- Underground hydrogen storage would have a dual role: on the one hand, to create strategic and seasonal storage to ensure energy sovereignty and, on the other hand, to ensure the baseload hydrogen demand of industrial consumers;
- Hydrogen transport and storage infrastructure can reinforce France's energy sovereignty at an optimal cost for French consumers.

Enabling implementation of the national hydrogen strategy and development of the electrolyser sector

The deployment of transport and storage infrastructure allows both the scale-up of renewable hydrogen production domestically and allows French electrolyser players to benefit from production projects beyond its national borders. Thus, they open up larger-scale prospects for French electrolyser manufacturers.

The results of the study show that the different infrastructure configurations have an impact on competitiveness, security of supply and access to a transmission and storage network for industrial players and hydrogen producers.

3.1 The role of hydrogen infrastructure in improving the competitiveness and attractiveness of national territories.

Infrastructure contributes to increasing the attractiveness of local territories for industrial companies. The presence of basic infrastructure such as telecommunication, road, or energy networks represents a crucial choice criterion for the establishment of factories in a given territory. With the increasing role of hydrogen in the industrial sector, transport networks and hydrogen storage infrastructures are also considered essential by the players already present in these territories but also by the new industrial players who wish to move there. This is a major factor of attractiveness. In this context, industrial players are closely following the direction of travel set by France in terms of its hydrogen infrastructure plan in order to have more visibility on the accessibility of this energy at the territorial level as well as on the evolution of prices.

3.2

Hydrogen infrastructure enhances system resiliency, security of supply, and national energy sovereignty.

The development of integrated and meshed hydrogen infrastructure, consisting of both a transport network and underground storage facilities, ensure better security of supply compared to an on-site hydrogen production system alone.

The transmission network balances production and consumption of hydrogen at the level of the industrial clusters and ensures continuity of supply, unlike in an isolated production system.

Centralised and large-scale storage, whether on a regional or national network scale, provides a higher level of security by ensuring continuous supply to industrial sites and contingency in case of unplanned power supply interruptions (short or long lasting of several weeks). As an example, unplanned interruptions to the gas system have been estimated at 4 seconds per customer in 2020.

3.3

Hydrogen infrastructure enables the implementation of the French national hydrogen strategy through supporting the development of a national electrolyser industry.

The national hydrogen strategy is focused in particular on the development of a national electrolyser manufacturing sector. The State is supporting several electrolysis production projects as well as electrolyser Giga-factories which will be deployed in the years to come.

The deployment of transport and storage infrastructure allows both the scale-up of renewable hydrogen production domestically and allows French electrolyser players to benefit from production projects beyond its national borders. Thus, they open up larger-scale prospects for French electrolyser manufacturers.

Zoom on Elogen

Elogen develops cutting-edge technologies to design and produce PEM (proton exchange membrane) electrolysers to produce green hydrogen.

With more than 15 years of expertise in the development of PEM electrolysers, Elogen relies on powerful R&D, a team of highly qualified engineers, and leading academic partnerships to continue to improve its solutions.

Since joining the GTT technology group in October 2020, Elogen has been committed to an industrial-scale ramp-up, which will enable it to reduce the cost of its electrolysers, and contribute to achieving French and European objectives for green hydrogen production.

Following the modernisation of its Les Ulis site in the Paris region, Elogen will have the largest electrolyser production capacity in France by early 2022, thanks to the installation of a pilot assembly line.

Innovation on the one hand and mass production on the other will enable Elogen to optimise the efficiency of its technologies and the competitiveness of green hydrogen, to better serve its customers in its various markets, in mobility, industry and energy storage.

With its cutting-edge technological solutions and as illustrated by the recent contract with Storengy for the HyPSTER green hydrogen storage project, Elogen will actively participate in the development of network and storage infrastructures that will help structure the hydrogen industry and improve its competitiveness.

4. The emergence of a no-regret development trajectory

Key messages

- A "no-regret" development trajectory begins with the assessment and implementation of dedicated hydrogen infrastructure, first within industrial clusters, then between clusters, and finally with interconnections to neighbouring regions – in line with the evolution of demand for renewable and low-carbon hydrogen;
- This trajectory for the constitution of dedicated infrastructures should favour the conversion of existing natural gas networks and storage facilities;
- To avoid stranded assets, infrastructure planning (especially within and between industrial clusters) must be carried out with a view on the longer-term vision of an interconnected infrastructure that will depend on demand from industry and in neighbouring countries. Strategic planning will be key;
- Considering the long deployment times for dedicated hydrogen transport and underground storage projects (about five years), it is crucial to develop a shared vision for the future and the associated infrastructure planning needed today, similar to the 10-year development plans for electricity and gas, to optimise investment decisions.

In the context of decarbonisation and industrial competitiveness desired by France, it is important to define and study future national hydrogen infrastructure strategies and scenarios. This work must be carried out in conjunction with policymakers and will be key to help provide French industrial players with the means to succeed in tackling the decarbonisation challenge. The aim of this work would be to establish a pragmatic trajectory for the deployment of hydrogen infrastructures that, on the one hand, avoids stranded assets and, on the other hand, favours the completeness and resilience of the system and the security of supply.

The design and development of a dedicated hydrogen transport and storage network is a process that will unfold in several stages according to the specific needs expressed by the various industries and regions.

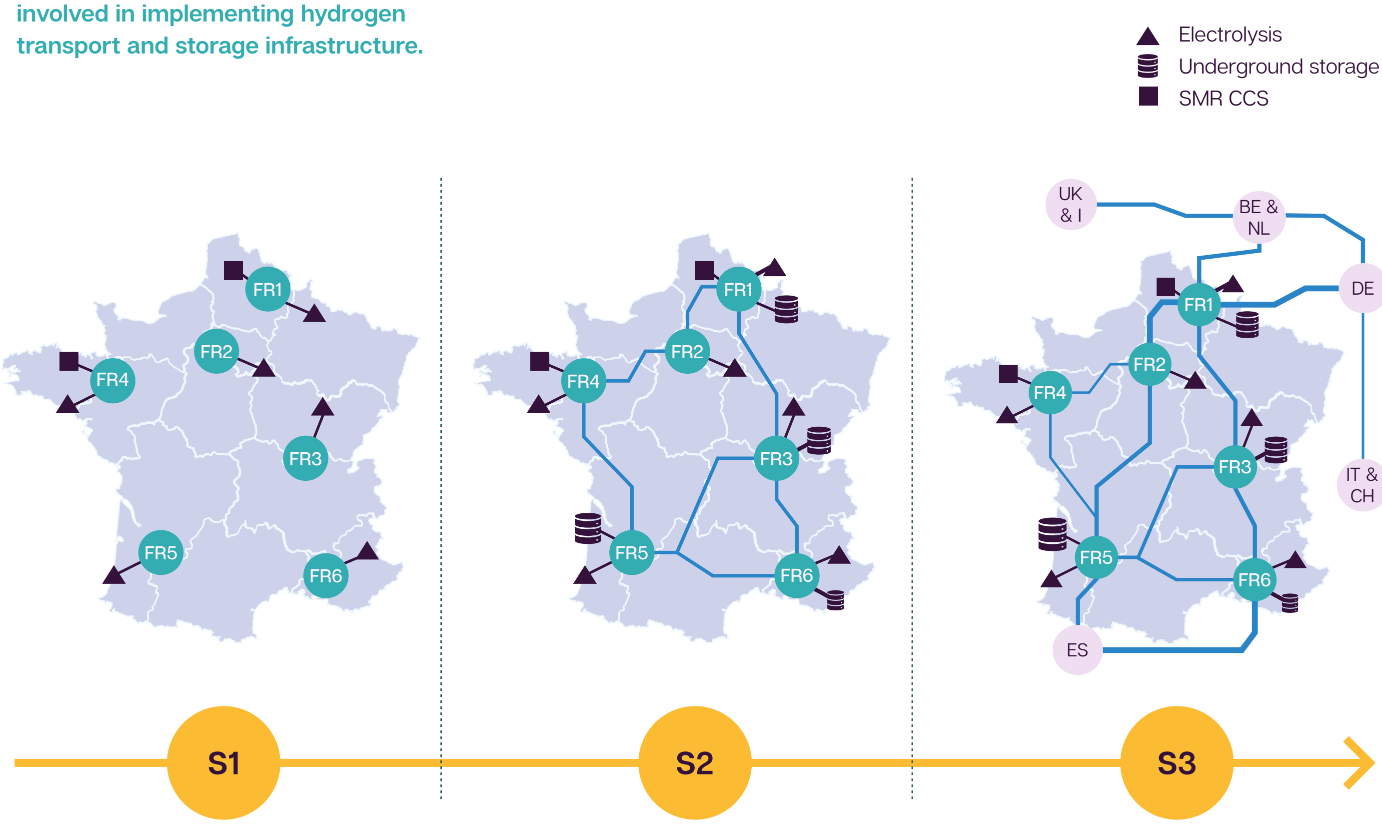
Industrial ecosystems integrated at the regional level will appear around existing regional infrastructure for production, demand, transport, and storage. This will give rise to the first needs to create connections that enable the transport and storage of hydrogen within territories. Gradually, these connections will stretch further to connect with other neighbouring sites but also to create links with more distant clusters across the French territory. This integration of several industrial clusters will lay the foundations for hydrogen infrastructure in France.

However, it is crucial to define this trajectory in view of the long-term decarbonised, interconnected, and integrated energy system – which will include a need for interconnections between regions and countries and a need for integration across power, hydrogen, and methane sectors. **Strategic planning is needed.** Storage planning will be particularly critical as the locations, sizes, and types of storage (salt caverns, aquifers, depleted gas fields) are unevenly distributed across the country.

The increase in hydrogen demand in France will be an important factor in the evolution of the transport and storage network at the national level but also at the European level. The foreseen hydrogen consumption needs of northern European countries such as Germany and the expected large-scale production of hydrogen in southern European countries such as Spain and Italy will determine the need and timing of establishing interconnections with neighbouring countries. These interconnections will bring several advantages to the French actors, including the possibility to access hydrogen at a competitive price and secondly to export French hydrogen to neighbouring countries with resource and capacity constraints such as Germany.

FIGURE 4

Illustrative flowchart of the steps involved in implementing hydrogen transport and storage infrastructure.



Source: Guidehouse

5. The commitment of European countries in the creation of dedicated hydrogen infrastructure

5.1 Several European countries are placing hydrogen infrastructure at the heart of their national hydrogen strategies.

European states are giving an increasingly important role to renewable and low carbon hydrogen in a future decarbonised energy mix and to maintain a competitive industry. Although early policy discussions have focused on production, most countries are beginning to consider how to ensure that hydrogen production is connected to demand. This is particularly the case in two types of countries:

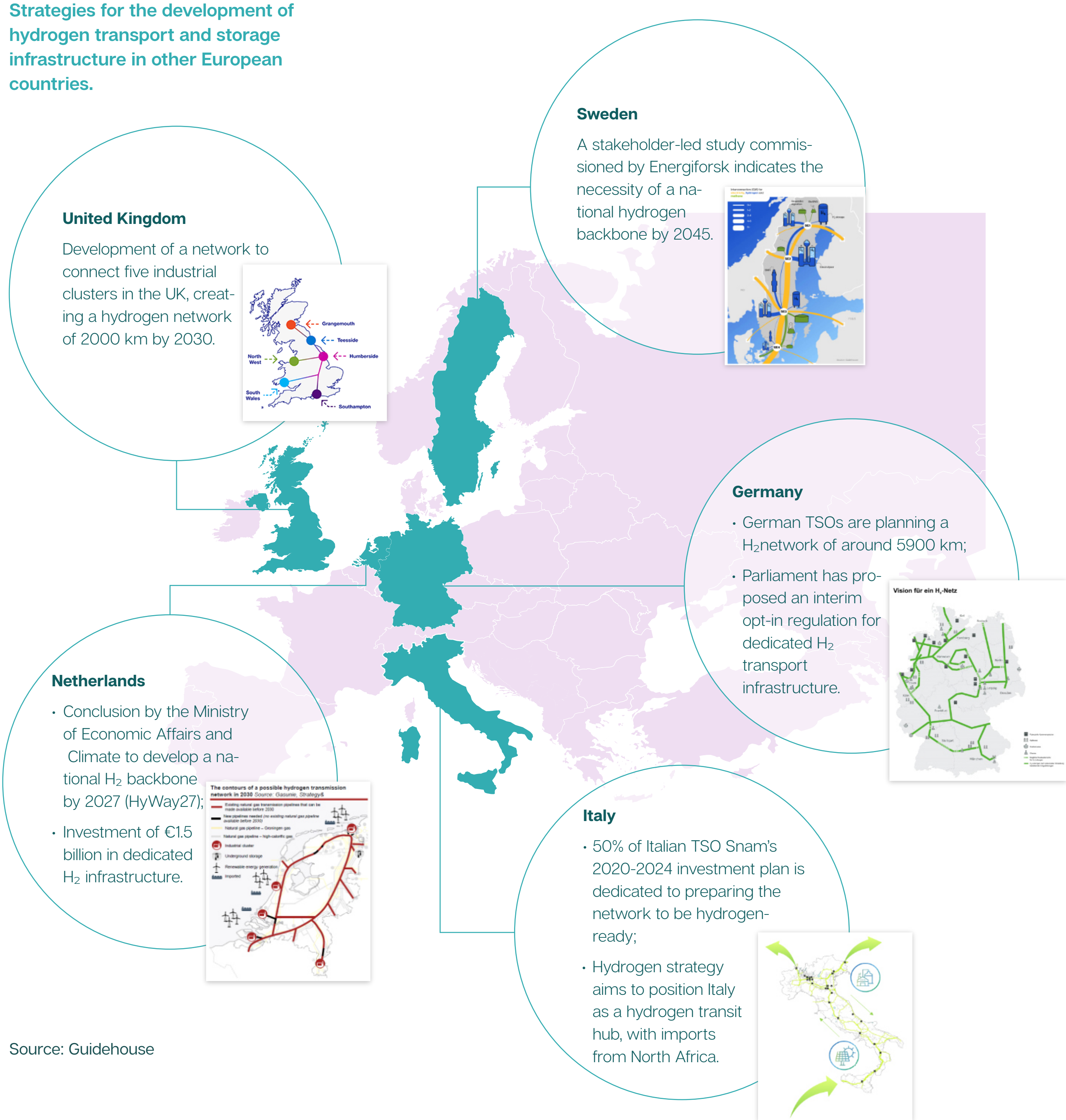
a) Countries where demand is high, but supply is limited, such as Germany and, to a lesser extent, Belgium, and the Netherlands.

b) Regions with significant renewable energy potential, such as the Nordic countries, the Baltic countries, and southern European countries like Spain and Italy.

Most of these countries have defined or are in the process of defining national hydrogen infrastructure strategies, with different approaches and time horizons - as summarized in Figure 5.

FIGURE 5

Strategies for the development of hydrogen transport and storage infrastructure in other European countries.



Source: Guidehouse

- In the Netherlands, the HyWay 27 detailed study conducted jointly by the Ministry of Economic Affairs and Climate, the Ministry of Finance and the electricity and natural gas transmission system operators was validated in June 2021. It highlights the interest of converting part of the Gasunie network and natural gas storage to hydrogen to connect 5 main industrial clusters and thus ensure flexibility and security of supply for consumers. Based on this study, the Dutch government asked Gasunie to launch this conversion, which represents an investment of 1.5 billion euros with a deployment date of 2027;
- In the United Kingdom, the development of a network is envisaged to link 5 industrial basins and thus create a network of more than 2000 kilometres;

- In Sweden, a country whose electricity mix is as decarbonized as France's thanks to nuclear power and hydroelectricity, a study by Energiforsk shows the need for a national hydrogen backbone linking hydrogen production sites and consumption centres by 2045;
- In Germany, the government has defined a hydrogen import strategy (>60% of demand) and proposed infrastructure for 2030 and 2035. The country will devote 2 billion euros to the development of partnerships with countries rich in renewable energy to enable renewable hydrogen imports to Germany;
- In Italy, over the period 2022-2024, 50% of the investments of SNAM, the natural gas transport operator, are dedicated to preparing the conversion of the network to hydrogen. The Italian government's stated strategy is to position the country as a "hydrogen hub to enhance exports/imports".

These national strategies of the European countries will have to be followed closely.

> **There are in fact two main strategies for producing green hydrogen. There is a strategy which consists of using renewable energies and electrolysis very far away and re-importing the hydrogen, a bit like we do with liquefied gas. There is a second strategy which is going to be the heart of ours: we are going to try to produce a lot of hydrogen in France because we have the possibility of doing electrolysis and, in addition, of doing electrolysis which is very low carbon. This is a huge opportunity, and it's what will allow us to be a leader. Besides that, we have very good research, we have very good players: Air Liquide and some other industrials. In addition, we have a network of start-ups, equipment manufacturers, entrepreneurs and innovators who are ready to go and who are organised.**
>
> Emmanuel Macron, President of the French Republic - Presentation of the France 2030 plan, 12 October 2021.[7]

Initially, cross-border interconnections are to be defined on a case-by-case basis with links that may be justified according to the evolution of production and demand. For example, Germany's growing demand will push the country to create interconnections to implement its hydrogen import strategy.

5.2 France is well-placed to be part of and benefit from an interconnected pan-European hydrogen network.

In the context of the development of hydrogen logistics in various European countries, France must build its own infrastructure to secure its future hydrogen market. This gives it an important potential and will allow it to enhance its geographical position and benefit from 2 advantages:

1. If France produces hydrogen at a competitive cost and with a sufficient level of security of supply, it can export to neighbouring countries with insufficient supply;
2. Given its geographical location, France is also well placed to benefit from imports and transits of hydrogen flows from Spain in particular, if they are more competitive, which can strengthen the competitiveness of French industry and help accelerate its decarbonization.

These conclusions depend on a progressive increase in the demand for renewable and low-carbon hydrogen, as shown by numerous studies. It will therefore be necessary to follow and account for the evolution of European countries that already have or are in the process of implementing hydrogen strategies including a transport and storage infrastructure component. France is well placed to participate and benefit from a pan-European interconnected hydrogen network.

7 Presentation of the France 2030 Plan, Speech by President Macron. https://www.elysee.fr/emmanuel-macron/2021/10/12/presentation-du-plan-france-2030.

6. Conclusions

To maximize the benefits on the competitiveness and implementation of the French hydrogen strategy, it is recommended to expand upon this work on two tracks:

- Working on seven optimisation paths that will enable maximisation of the benefits of the infrastructure;
- Continuing and deepening these studies and constituting a planning work in collaboration with the State and a wider set of contributing stakeholders in a sectoral integration approach.

6.1 Seven complementary optimisation levers to maximise benefits to industry and enable implementation of the national hydrogen strategy.

Following this initial study, seven optimisation levers, listed below, have been identified to maximise the benefits of hydrogen infrastructure and optimise the total investment cost.

1. Collaboration with power and gas transport companies to optimise investments in power, gas, and hydrogen infrastructure in an integrated manner;
2. Assessment of trade-offs between existing and new infrastructure to maximise repurposing potential and optimise costs;
3. Optimisation, scale-up, and integration of large-scale renewable energy capacities (offshore wind, onshore wind, solar PV) in conjunction with nuclear production;
4. Development of underground hydrogen storage for local and inter-regional use;
5. Definition of transition trajectories within industrial clusters, between industrial clusters, and with European interconnections for 2030, 2040, and 2050 – in step with market demand;
6. Utilisation of low-carbon hydrogen production by SMR CCS (conversion of existing SMR production units with CCS as well as new units);
7. Collaboration with neighbouring countries and the EU to identify transit needs and secure the associated investment needs.

6.2 Next steps and future work in collaboration with the Government

It is recommended that this work should be continued, collaborating with the State in the framework of the French Strategic Committee of the Industry (Comité Stratégique de Filière Nouveaux Systèmes Énergétiques, CSF NSE):

1. Electricity market players should be integrated more widely, particularly the transmission system operator, alongside major relevant industrial consumers of low-carbon hydrogen, the central pillars of the French basins, and the producers of electrolysers who have expressed their wish to do so;
2. Longer-term strategic planning should be undertaken so that the initial investments in the clusters serve the longer-term vision. The results of this work on infrastructure planning scenarios and associated benefits and investments could feed into the future Multiannual Energy Programme ("Programmation Pluriannuelle de l'Énergie") and can be acceleration levers for implementation of the National Hydrogen Strategy.

Appendix

Glossary

ATR	Autothermal reforming
CAPEX	Capital expenditures
CCS	Carbon capture and storage
DRI	Direct Reduced Iron
ENTSO-E	European Network of Transmission System Operators
LCOH	Levelised cost of hydrogen
PCI	Lower heating value
PPE	Multiannual energy planning
PSA	Pressure swing adsorption
SMR	Steam methane reforming
TYNDP	Ten year- network development plan
WACC	Weighted average cost of capital

Assumptions

A. Hydrogen demand in France

Afin de rester cohérents avec les hypothèses adoptées par les autres études menées sur le sujet, une hypothèse de demande de base a été formulée en accord avec France Hydrogène. La répartition par secteur est présentée dans le tableau 2 ci-dessous.

TABLE 2

Baseline demand assumption.

		2030		2035		2040	
		kt	TWh	kt	TWh	kt	TWh
Industry	**Steel**	205	6.8	278	9.2	351	11.6
	Ammonia	60	2.0	190	6.3	320	10.6
	Refinery	122	4.0	82	2.7	42	1.4
	Heavy chemicals	22	0.7	38	1.3	54	1.8
	Synthetic fuel	56	1.8	158	5.2	261	8.6
	Diffuse industry	12	0.4	119	3.9	227	7.5
	Subtotal	477	15.7	865	28.5	1255	41.4
Transport	**Road transport**	108	3.6	169	5.6	229	7.6
	Large marine	19	0.6	28	0.9	37	1.2
	Inland waterway transport & coastal navigation	7	0.2	10	0.3	13	0.4
	Railway	14	0.5	20	0.7	26	0.9
	Subtotal	148	4.9	227	7.5	305	10.1
Electricity		45	1.5	103	3.4	160	5.3
Heating of buildings		0	0.0	20	0.7	40	1.3
Total		**670**	**22.1**	**1215**	**40.1**	**1760**	**58.1**

Source: Guidehouse, analysis by industrial site and based on interviews with industrial stakeholders and associations.

A high demand assumption was also evaluated, as shown in Table 3.

TABLE 3

High demand assumption.

		2030		2035		2040	
		kt	TWh	kt	TWh	kt	TWh
Industry	**Steel**	205	6.8	319	10.5	511	16.9
	Ammonia	60	2.0	291	9.6	364	12.0
	Refinery	122	4.0	39	1.3	0	0.0
	Heavy chemicals	203	6.7	452	14.9	801	26.4
	Synthetic fuel	184	6.1	777	25.6	978	32.3
	Diffuse industry	113	3.7	206	6.8	243	8.0
	Subtotal	887	29.3	2083	68.7	2896	95.6
Transport	**Road transport**	209	6.9	403	13.3	637	21.0
	Large marine	45	1.5	78	2.6	104	3.4
	Inland waterway transport & coastal navigation	15	0.5	26	0.9	35	1.1
	Railway	32	1.1	55	1.8	74	2.4
	Subtotal	301	9.9	561	18.5	849	28.0
Electricity		129	4.3	667	22.0	1818	60.0
Heating of buildings		0	0.0	30	1.0	152	5.0
Total		**1317**	**43.5**	**3342**	**110.3**	**5715**	**188.6**

Source: Guidehouse, analysis by industrial site and based on interviews with industrial stakeholders and associations.

B. Hydrogen demand in neighbouring regions

The assumptions adopted for demand in other European countries are taken from the European Hydrogen Backbone (EHB) study.

TABLE 4

Hydrogen demand in neighbouring regions.

	2030		2035	
	kt	TWh	kt	TWh
Germany	2273	75	8636	285
Netherlands	848	28	2667	88
Belgium	606	20	1939	64
United Kingdom	1061	35	4576	151
Italy	970	32	4727	156
Spain	1000	33	3152	104

Sources: European Hydrogen Backbone, Analysing future demand, supply, and transport of hydrogen (2021).

C. Evolution of existing electricity generation capacities

The evolution of existing electricity generation capacities is consistent with RTE's N1 "RE + nuclear" scenario, which is compatible with the national EPP 2028 plan. This scenario foresees the development of renewable energies and new EPR reactors in pairs, with a commissioning rate of approximately one pair every five years from 2035.

TABLE 5

Evolution of existing electricity generation capacities.

	2020	2028	2030	2035	2040
Existing nuclear	61	56	56	47	43
New nuclear power	0	0	0	3	7
Onshore wind	18	35	38	45	54
Offshore wind	0	5	6	9	24
Solar PV	11	40	42	52	57
Thermal	18	16	13	7	4
Hydroelectricity	24	26	27	27	28
Bioenergy	2	3	2	3	3
Total	134	181	184	193	220

Source: RTE, "Energy Futures 2050" long-term forecast (2021).

D. Hydrogen production cost assumptions

TABLE 6

Hydrogen production cost assumption.

Parameter	Unité	2030	2035	2040
Electrolysis - CAPEX	€/kW,el	560	410	260
Electrolysis - OPEX	€/kW,el-an	18	14	13
Electrolysis - efficiency	%	71%	73%	76%
SMR CCS - CAPEX	€/kW,H_2	1200	1200	1200
SMR CCS - OPEX	% de CAPEX/an	3%	3%	3%
CCS SMR - capture rate	%	90%	90%	90%
SMR CCS - CO_2 transport and storage	€/tCO_2	50	50	50

Source: Agora Energiewende, "No Regret Hydrogen" ; IRENA, "Green Hydrogen Cost Reduction"; ASSET, "Hydrogen Generation in Europe"; H-Vision.

TABLE 7

Hydrogen production cost assumptions.

E. Electricity production cost assumptions

Technology	Parameter	Unit	2030	2035	2040
Onshore wind	CAPEX	€/kW	1000	900	800
	OPEX	€/kW-year	36	35	34
	Capacity factor	hours/year	Varies by region modelled.		
Offshore wind	CAPEX	€/kW	1300	1100	995
	OPEX	€/kW-year	95	91	87
	Capacity factor	hours/year	Varies by region modelled.	90%	4
Solar PV	CAPEX	€/kW	500	400	330
	OPEX	€/kW-year	10	9	8
	Capacity factor	hours/year	Varies by region modelled.		
Thermal	CAPEX	€/kW	750	750	750
	OPEX	€/kW-year	15	15	15
	Capacity factor	hours/year	Varies by region modeled.		

Source: Guidehouse Insights, Renewables .ninja, ENTSO-E.

F. Hydrogen transport cost assumptions

TABLE 8

Costs of natural gas pipelines converted for hydrogen transport.

The assumptions concerning the availability and conversion capacity of natural gas pipelines have been discussed with the French gas infrastructure operators and are in line with the assumptions made in the EPP.

		Diameter		
Parameter	**Unit**	**500 mm / 20 inch**	**900 mm / 36 inch**	**1200 mm / 48 inch**
Operational pressure	Bar	50	50	80
Capacity	GW H_2 (LHV)	1,2	3,6	13
Capex pipeline	M€/km	0,3	0,4	0,5
Open pipeline	% of new Capex/ year	0,5-1,7%		
Compressor	MWe/1000km	26	40	183
Capex compressor	M€/MWe	3,4		
Opex compressor F.	% of Capex/year	4%		
Opex compressor V.	€/MWh	50		

Source: European Hydrogen Backbone (2021).

TABLE 9

Costs of new hydrogen pipelines.

Parameter	Unit	Diameter		
		500 mm / 20 inch	900 mm / 36 inch	1200 mm / 48 inch
Operational pressure	Bar	50	50	80
Capacity	GW H_2 (LHV)	1,2	4,6	13
Capex pipeline	M€/km	1,5	2,2	2,8
Open pipeline	% of new Capex/ year	0,5-1,7%		
Compressor	MWe/1000km	26	40	183
Capex compressor	M€/MWe	3,4		
Opex compressor F.	% of Capex/year	4%		
Opex compressor V.	€/MWh	50		

Source: European Hydrogen Backbone (2021).

G. Power transmission cost assumptions

TABLE 10

Transmission cost assumptions.

Parameter	Unit	HVAC	HVDC	Source
Voltage	kV	380	800	CIGRE Technical Brochure 775 (2019)
Power rating	MW/MVA	2800	8000	CIGRE Technical Brochure 775 (2019)
CAPEX – low	k€/km/GW	130	180	CIGRE Technical Brochure 775 (2019)
CAPEX – high	k€/km/GW	250	330	CIGRE Technical Brochure 775 (2019)
CAPEX – ACER	k€/km/GW	200-500	300-450	ACER (2015), used by RTE
OPEX	% of CAPEX/ year	1%	1%	e-HIGHWAY 2050 ENTSO-E (2012)
Line losses	%/100km	1,10%	0,15%	Siemens (2014) & VDE Kassel (2016)

Sources : CIGRE, ACER, ENTSO-E, Siemens, VDE Kassel.

H. Hydrogen storage cost assumptions

TABLE 11

Cost of hydrogen storage in salt caverns according to different literature sources.

Source / Study	Cost of hydrogen storage, €/kg
R.K. Ahluwalia et al (2019)	0,18
Bloomberg (2020)	0,23
M. Reuß et al (2017)	0,70
DNV GL (2020)	0,35

TABLE 12

Costs of Hydrogen Storage in Aquifers.

Parameter	Unit	Value
Cost per well	€	3 000 000
Flow rate per well	Nm3/h	100 000
Cost per ASP	€	160 000
Flow rate per PSA	tH_2/day	1,0
Cost per separation membrane	% CAPEX PSA	10%
Cost per booster	€	1 000 000
Storage capacity	Mm3 (60 bar)	30
Number of wells	#	10
OPEX PSA and membranes	% CAPEX	2%
OPEX storage site	€/TWh/year	1 200 000

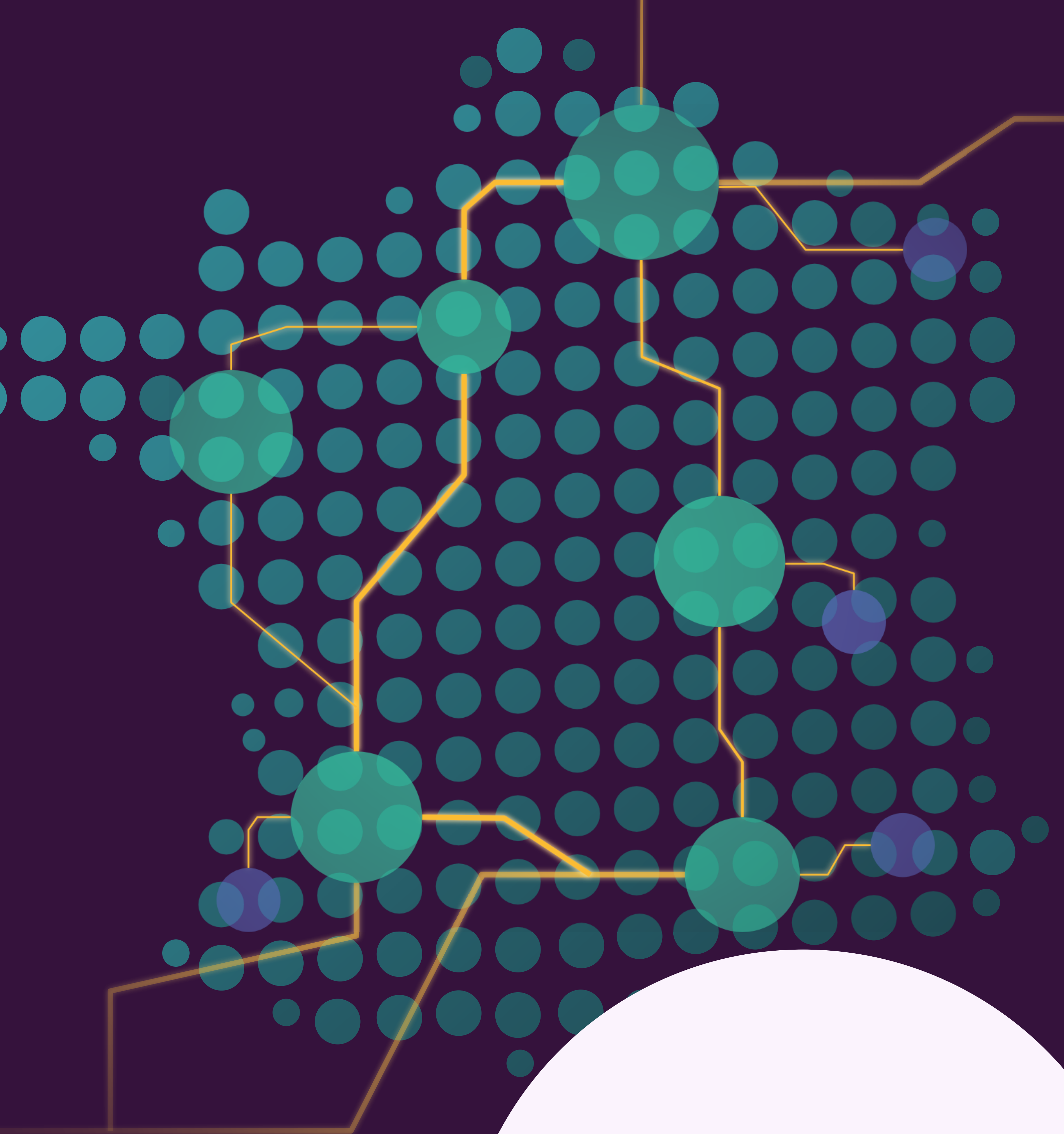
Sources: Guidehouse analysis.

TABLE 13

Delivered Hydrogen Cost and Cumulative Capital Costs for the Two Demand Assumptions.

'High' demand assumption results

Parameter	Demand assumption	S1: Isolated national ecosystems			S2: Integrated national ecosystems			S3: National and European Ecosystems		
		2030	2035	2040	2030	2035	2040	2030	2035	2040
LCOH, €/kg H_2	**Basic assumption**	3.2	2.9	2.8	2.9	2.7	2.7	2.7	2.2	1.9
	High hypothesis	3.0	2.7	2.7	2.8	2.7	2.7	2.7	2.3	1.9
Investments, € billions	**Basic assumption**	3.3	7.4	16.1	3.0	6.4	13.1	7.2	12.3	17.7
	High hypothesis	7.2	14.4	26.2	6.1	10.6	19.5	8.2	13.9	19.2



An initiative by GRTgaz, HDF Energy, Soladvent, Storengy, Teréga, TotalEnergies

Within the Comité Stratégique de Filière Nouveaux Systèmes Énergétiques (CSF NSE)