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Impact of wind-hydrogen plants on energy systems and RCS

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Abstract: In order to evaluate the Haeolus concept in the European context, the impact of wind-hydrogen systems in the European energy system is evaluated. EMPIRE model (a mixed integer linear programming model, MILP) is used to perform the analyses for a different number of future scenarios. The model calculates the optimal European energy system with the lowest costs until 2050. As a factor influencing the acceptance and future uptake of new energy solutions, policy and regulations affecting wind-hydrogen systems are discussed. Thus, the regulations, codes and standards for specific hydrogen fuel cell applications that are considered relevant in the Haeolus concept to identify and assess legal-administrative drivers and barriers are identified and reviewed.

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Executive summary

In this deliverable, the impact of wind-hydrogen systems in the European energy system is evaluated. In order to perform the analyses, the EMPIRE model is used. This model uses mixed integer linear programming (MILP) and it is programmed in Pyomo, a Python optimisation package and calculates the optimal European energy system with the lowest costs until 2050. The model initially does not include hydrogen in the system and thus it has been expanded to include this possibility.

As a factor influencing the acceptance and future uptake of new energy solutions, policy and regulations affecting wind-hydrogen systems are discussed. An overview of climate and energy policies and the regulatory frameworks surrounding hydrogen-wind systems is presented. Subsequently, regulations, codes and standards for specific hydrogen fuel cell applications that are considered relevant in the Haeolus concept are enumerated and discussed to identify and assess legal-administrative drivers and barriers.

Finally, the effect of hydrogen and wind in the European energy system has been analysed for a different number of scenarios. It has been considered various hydrogen future demands, two sets of countries that have hydrogen demand and are allowed to install hydrogen systems, and the obligation to cover the demand or not.

The main takeaways of the EMPIRE scenarios are summarised in the following bullet points:

- Hydrogen is not profitable by itself as a storage method, thus demand satisfaction for the fuel must be forced for it to enter the energy system.
- Once in the system, it is widely used as storage, becoming the main storage technology to cover the fluctuation from extra renewable energy needed to produce the required hydrogen, representing up to 24 % of the storage discharge energy in 2050.
- Incorporating Hydrogen demand into the current European electricity system involves significantly large investments in generation capacity to cover this extra demand, which EMPIRE tries to cover mainly by solar and wind.
- The introduction of Hydrogen, and its increase in generation capacity, impact only the larger links in the transmission system. The rest of the network remains largely as it would to cover electricity demands without introducing hydrogen, with limited exceptions. There is no significant difference when it comes to hydrogen in selected countries (Norway, Germany, Spain) or in all European countries.
- The Ambitious demand scenario, when all countries are forced to satisfy the demand, almost doubles the overall cost of the electricity system. However, even at a price of 2.5Euro/Kg H_2, sales from hydrogen would almost be enough to offset the capacity costs.
- Finally, if the model is forbidden from investing heavily in solar power to approach more closely a Haeolus concept, the model opts for both wind modalities to take up the slack, though this incurs in a raise of about 9 % in production costs.

Table of Contents

List of Figures

List of Tables

Acronyms and glossary of terms

AAI: Autorización Ambiental Integrada (Integrated Environmental Authorisation)

ADR: European Agreements Concerning the International Carriage of Dangerous Goods by Road

AFID: Alternative Fuels Infrastructure Directive

aFRR: automatic Frequency Restoration Reserve

AiP: Approval in Principle

AND: EU directive on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport

ATEX: Equipment for potentially explosive atmospheres

CAPEX: Capital expenditures

CCS: Carbon Capture and Storage

CCUS: Carbon Capture, Utilisation and Storage

CHP: Combined Heat and Power

CNG: Compressed Natural Gas

CNMC: National Commission on Markets and Competition

CO_2: Carbon dioxide

CSV: Comma-Separated Values

DGT: Dirección General de Tráfico (Directorate-General for Traffic)

DGTT: Dirección General del Transporte Terrestre (Directorate General for Road Transport)

DSB: Directorate for Civil Protection

DSO: Distribution System Operator

EC: European Commission

ECA: European Court of Auditors

EIA: Environmental Impact Assessment

ETS: Emissions Trading System

EU: European Union

FCR: Frequency Containment Reserve

GHG: Greenhouse Gas

GO: Guarantee of Origin

GPP: Green Public Procurement

H_2: Hydrogen

HRS: Hydrogen Refuelling Station

IED: Directive on Industrial Emissions

ISO: International Organisation for Standardisation

IGC: International Gas Carrier

IMDG: International Maritime Dangerous Goods

IMO: International Maritime association

LNG: Liquefied Natural Gas

MAN: National Action Framework for the development of the market and the infrastructures for alternative fuels in the transport sector.

MARPOL: International Convention for the Prevention of Pollution from Ships

mFRR: manual Frequency Restoration Reserve

MILP: Mixed Integer Linear Programming

MINLP: Mixed Integer Nonlinear Programming

MIP: Mixed Integer programming

NBM: Nordic Balancing Model

NECP: Integrated National Plan for Energy and Climate

NLP: Nonlinear Programming

NVE: Norwegian Water Resources and Energy Directorate

OPEX: Operational expenditures

PEM: Proton Exchange Membrane

RC: Revenue Cap

RED: Renewable Energy Directive

REE: Red Eléctrica de España (Spanish transmission system operator)

RID: European Agreements Concerning the International Carriage of Dangerous Goods by Rail

SEA: Strategic Environmental Assessment

SET-plan: Integrated Strategic Energy Technology Plan

SEVESO: Directive on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC

SNG: Substitute Natural Gas

SOLAS: Safety of Life at Sea Convention

SP: Stochastic programming

TEP: Transmission Expansion Planning

TPED: Transportable Pressure Equipment Directive

TSO: Transmission System Operator

T&D: Transmission and Distribution

UN: United Nations

VAT: Value Added Tax

1 The Haeolus Concept

The Haeolus concept is based on two main ideas: to produce green hydrogen by means of large-scale wind power, and to find the best way to market such hydrogen. The Haeolus concept is supported by a pilot plant consisting on a previously existing 45 MW wind farm, a 2.5 MW proton exchange membrane (PEM) electrolyser and a 100 kW fuel cell (together with hydrogen storage and extra installations required), all located on the Raggovidda plateau, near the town of Berlevåg (Finnmark, northern Norway).

A key issue with this idea is the fact that good remote-wind production is expensive to connect to a land-network; thus, produced energy should be either used, stored or moved in ways that justify costs. Hence, hydrogen arises as a technically feasible alternative to employ the considerable wind power. The Haeolus project then deals with the technical difficulties, possibilities of marketing, and wider implications of a successful implementation of the concept.

The work presented in this deliverable covers the last point. This section presents some precedents and technical details surrounding the idea behind the project. Section 2 describes the European electricity network and the modelling approach, while section 3 deals on the model used to run the analyses, EMPIRE. Section 4 describes policy and legal issues surrounding the concept. In section 5, the potential impacts of the concept by means of the study of the effect of hydrogen and wind production in the European electricity system are presented. Finally, in section 6 some concluding remarks, future work and recommendations on ways forward in both the Haeolus project and beyond are given.

1.1 Hydrogen Production

Hydrogen is a good solution for large-scale production and long-term storage of renewable wind energy for remote locations, and even more in regions of reduced/unfeasible access to national grids. Generating hydrogen by electrolysis stores energy in a carrier that can either be converted back to energy when there is demand, or sold as fuel or chemical feedstock [1].

Electrolysers can be started and stopped within few seconds, and can provide reserve services to stabilise remote grids by ramping up or down as required, improving grid reliability [2]. Haeolus tests a latest-generation, ultra-compact 2.5 MW PEM electrolyser, with excellent dynamic properties, able to support the grid in any time scale. These grid services could be a significant side income for hydrogen production plants and often decisive for the economy of the plant.

The availability of hydrogen fuel in the area can then spur the adoption of hydrogen-based zero-emission solutions for transport in the area: in Haeolus' case fishing boats, ferries, trucks, buses and even regional planes are being considered with the cooperation of municipal and county authorities.

Projections indicate that hydrogen cost in a full-scale deployment of Haeolus technology may be as low as 2 €/kg, providing significant profit margins to the operators. Norwegian hydrogen refuelling stations operate with a selling price of about 9 €/kg [3].

Currently, the plant is under construction and not generating revenue. A challenge for the first months of the production run is to find customers willing to buy the produced hydrogen and the lack of hydrogen infrastructure. This is being pursued by developing clean-energy initiatives in the region in coordination with local authorities.

Owners of renewable power plants are the immediate targeted market for Haeolus technology. Many utilities across Europe and worldwide have come to terms with the unpredictable nature of wind power generation and the difficulties it causes to grid stabilisation.

Further in the timeline, dedicated hydrogen production companies may arise that will exploit Haeolus technology to provide grid-balancing services as an additional income; indeed, our partner Varanger Kraft has already spun off such a company.

As a chemical feedstock, hydrogen plays or could play an important role in the production of basic substances such as methanol and ammonia. The economics of each are different, but overall both have potential for CO_2 savings if the hydrogen is produced by electrolysis, as in Haeolus. While there are admittedly cheaper and also other green ways to produce the chemicals, they often involve transport over great distances (such as natural-gas rich ones in Northern Africa), or access to solar energy (to substitute the windfarms if available), which makes local production desirable. [4]

1.2 The Raggovidda Test Site

The Haeolus consortium decided to locate Hydrogenics' 2.5 MW electrolyser in the Berlevåg harbour area, which is planned to become an industrial park in the near future. The location makes it possible to integrate the electrolyser with other future industries and allows relatively easy export possibilities compared to a location on the Raggovidda plateau where the wind park is located.

Berlevåg harbour is accessible by sea year-round, even though its position is exposed to the Barents Sea, and access may be difficult for larger ships on particularly windy days. Finnmark's county road 890 passes in front of the electrolyser site and has recently been upgraded; it is usable year-round to access the Norwegian road network, even though convoys need to be formed in winter to pass the Hanglefjellet mountain range between Berlevåg and Tana.

The electrolyser will be able to produce 1 ton of H_2 per day and will be connected directly to the Raggovidda wind park; if energy from the wind park were insufficient to meet target production, power from the grid can be used. Haeolus committed to a total production of 120 tons over 30 months [5].

2 The European Energy System

The transmission and distribution networks comprise the set of assets that support the transfer of energy from generating units to the demand. The transmission grid deals with the long-distance transfer of large amounts of electricity and its typically relatively meshed so that it behaves as a single global entity. Distribution grid has a more local nature and delivers power from substations to demand nodes. In the countries comprising the Interconnected network of Continental Europe, transmission uses mainly high-voltage assets of 132, 220 and 400 kV. Distribution includes assets with voltages below 32 kV. One of the main issues determining the future grids is whether the renewable generation that should be installed to comply with long-term European targets is installed in a centralised or decentralised manner [6].

In a centralised future, most of the necessary renewable generation will be installed as large-capacity plants, comprising for instance onshore and offshore windfarms. These generation plants would benefit from the economies of scale that result from large capacities. In addition, they could take advantage of stronger market integration among the Member Countries, as it would be possible to benefit from better renewable potentials in some geographical areas and export the energy to less-favoured countries. In contrast, a decentralised scenario would make extensive use of rooftop PV and other small-scale generation technologies. The system would then be comprised of consumers that would be close to being self-sufficient. In such a scenario, the grid is still on charge of providing the necessary reliability to the system [6].

Storage of energy is a crucial technical issue in a grid system which is more and more dependent on solar and wind power. Battery technology is still expensive, though useful for small-scale applications. Pumped hydro is by now a reliable technology for this purpose but is limited in its application to countries with suitable hydrography, such as Switzerland and Norway. Hydrogen's role as means of storage is relevant to the entire European network as, safety issues resolved, it has the potential to become a cost-effective, long-term solution for storage and transport of energy, either in the form of hydrogen itself, or as ammonia [4].

2.1 Modelling Approach

To model the European Electricity System, the EMPIRE optimisation model [7] has been used. As an optimisation model, it aims to minimise the total cost of the European electricity system with enough energy to satisfy an exogenously given demand. Broadly speaking, EMPIRE is intended to model the period from 2015 to 2050, and the entirety of Europe. In practice, however, this period and coverage can be modified to suit relevant purposes.

The costs of the system encompass several sources, including strategic (investments on generation, connection links, storage options) and operational (running generators, emission costs, Carbon Capture and Storage, CCS). Optionally, the model can also define demand to be covered and prices for energy; in this way, sales can be added to the objective function to off-set costs. Constraints in the model include limits on investment on generators and storage, balancing of the load in each node and at every hour, definition of flow between regions, limits on the ramp up ability of certain technologies, and definition and operation of the storage alternatives (energy levels, charge, discharge, and relationship to the node load balance.) The model simplifies some of the physical processes, such as Kirchhoff laws, nonlinear battery leakage, as well as obviating inter-node networks. These omissions are a technical requirement, as a model trying to capture such a large system would result very resource- and time-consuming to solve numerically if all aspects were considered.

It is important to note that EMPIRE optimises the system as though a single actor took all decision, was responsible for all operations, and paid all costs. Thus, the result assumes full cooperation between the individual actors of every element. In praxis this is clearly unrealistic. Nevertheless, a solution given by EMPIRE is not only technically possible (with caveats derived from the simplifications noted above), but also an encouragement for actors to cooperate.

3 The EMPIRE Model

Linear programming is a powerful and efficient algorithm that can be applied to large-scale problems. However, some important simplifications must be adopted in order to be able to use this method. The most important one is that the discrete nature of investments must be ignored. In addition, the Second Law cannot be incorporated, and power-flow modelling must be approximated using only transportation power flows [6].

Mixed-Integer Programming (MIP), on the contrary, correctly models the discrete nature of investment and can approximate power flows using a DC load flow, where active power flows are reasonably estimated. Linear approximations of losses can also be considered. Most academic and practitioner works dealing with transmission expansion planning (TEP) rely on MIP as their main technique. Nonlinear Programming (NLP) and Mixed-Integer Nonlinear Programming (MINLP) can accurately capture AC power flows. However, the computational complexity they entail is only justified in some specific cases, mainly when reactive power flows play a key role in the final expansion result. This only happens rarely, so there are only a few works that use this type of methods [6].

The incorporation of uncertainty, mainly in the consideration of different scenarios for renewable power generation, is increasingly important to get representative results. The inclusion of many of such scenarios makes it interesting to explore the possibilities of Stochastic Programming (SP) and decomposition algorithms [6].

3.1 Implementation

EMPIRE is implemented in Pyomo, an algebraic modelling module/extension of the Python script language. Python is a flexible, general-purpose programming language widely employed in scientific applications thanks to its versatility and large number of modules for numerical calculations, graphic output, database and spreadsheet interfacing, and access to powerful commercial solvers. Pyomo is a Python module which allows for mathematical optimisation problems to be written in expressions closer to symbolic mathematics, similar to other algebraic modelling languages like FICO Mosel, GAMS, and AMPL.

All expressions characterising the EMPIRE model are coded in Pyomo, which reads several comma-separated-value (CSV) files in which all information regarding the problem is held. This includes generation technology parameters, network design, storage specifications, emissions, investment and operation costs, wind/solar/hydro time series, demand time series, and so on.

Python/Pyomo use the commercial solver FICO Xpress to find an optimal solution to any EMPIRE instance, if such exists. Xpress is a proprietary, black-box style part of the solution process, which means the user has little control (compared to other parts of the framework) to determine how it works, but the model also allows substituting Xpress with any other solver with the same interface if needed. However, there is no need not worry too much about efficiency since the solver itself is market-leading in terms of speed and memory management.

Results are exported to CSV files which can then be read by any plain text or spreadsheet software to be reported or plotted. Results can also be exported to Tableau-style software, though this has not been contemplated.

3.2 Node Addition and Simplification

In the latest EMPIRE dataset available, Norway is divided into five different, interconnected nodes, each representing one of the Statnett trading zones [8]. All other European countries are represented as a single node. Norwegian nodes NO1 to NO5 are independently connected to other countries.

To add the Haeolus concept to the model, six nodes have been selected to be the mayor producers and consumers of hydrogen in the future: NO2 to NO4, Spain and Germany. This node group represents the 'Selected' nodes used later in the analysis with EMPIRE. Then, the main nodes connected to these main hydrogen nodes are represented as individual nodes as well (Sweden, France, Belgium etc.). The other original EMPIRE nodes are then aggregated into one 'Europe' node. This node distribution is shown in Figure 1.

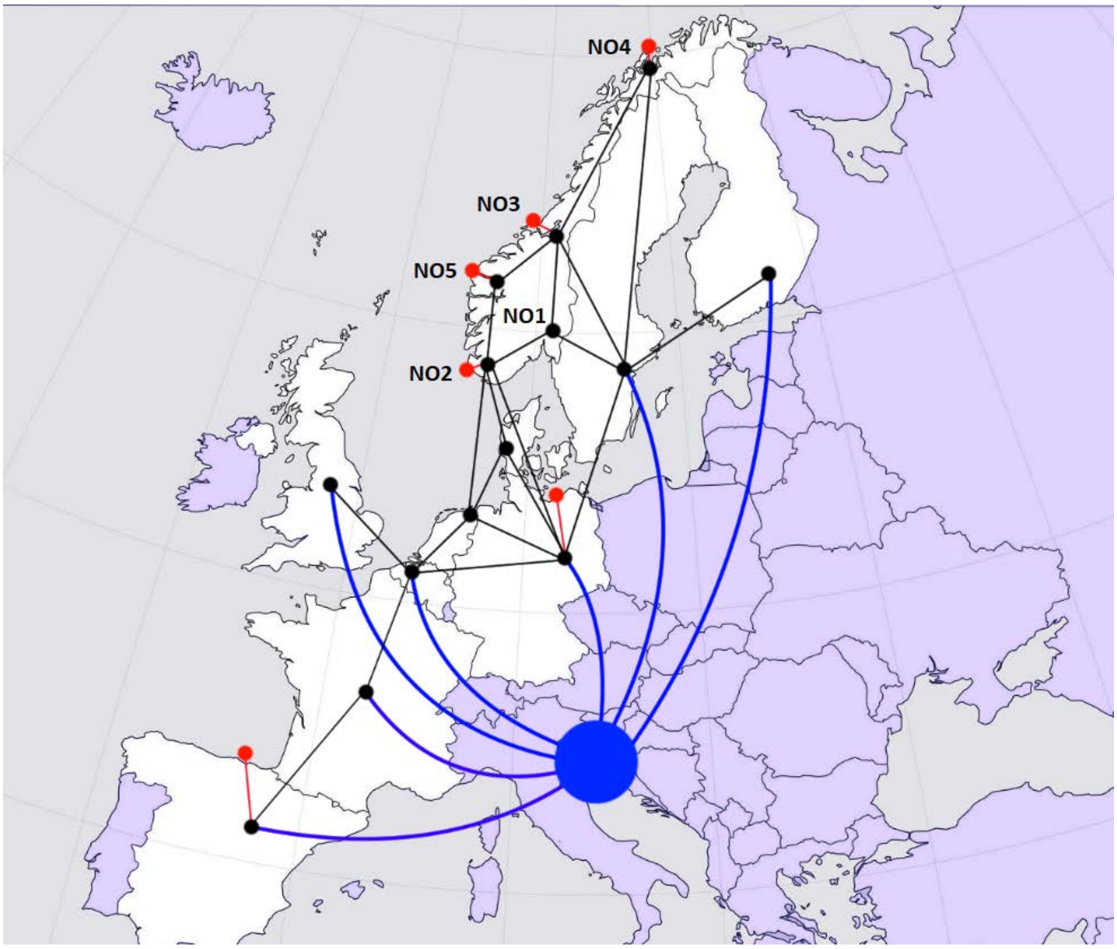

Figure 1: Nodes of the EMPIRE model, with the aggregated European node (dark blue) and the selected Haeolus nodes (red, belong to the black node they are connected to).

3.3 Hydrogen Modelling

The original EMPIRE modelling has been changed for allowing the inclusion of hydrogen. In general, at any node, hydrogen can be produced, sold, and employed as storage, neither of which is allowed in the original formulation.

Production of hydrogen is simplified, as are all other sources, and mainly include energy as input for the process. Because the relevant Haeolus concept only consider electrolysis as hydrogen source, no natural gas reformation is considered or modelled in this version of EMPIRE.

The hydrogen produced can be used as storage of energy. This means hydrogen is modelled in the same way other storages in EMPIRE are (including batteries and pumped hydro reservoirs). Thus, it is possible to invest in charge/discharge power (representing the PEM electrolyser and fuel cell capacity) and in energy storage (representing the hydrogen storage). Its technical details (leakage, efficiency, etc.) are left for each case to determine, but are expected to match real-world values. Technically all nodes are allowed to use hydrogen as storage, just as they are allowed to buy batteries, but just as with pumped hydro, not all nodes can *in practice*, use the technology (for example, because there are no ways to get the hydrogen to these nodes in the real world).

Finally, hydrogen can leave the node where it is produced as a sale. Sale prices of hydrogen are exogenous parameters, as are all prices in EMPIRE, and thus the model is dependent on relevant market values to decide whether to sell hydrogen or not in Raggovidda or any other node in which production can occur.

4 Policy and Regulations

The impact of hydrogen-wind systems will also depend on climate and energy policy and regulatory frameworks. This chapter provides an overview of regulations, codes and standards pertaining to hydrogen-wind systems and the applications of hydrogen that currently seem most relevant for the Haeolus concept.

After a brief presentation of the applied mapping and assessment method, a general overview of climate and energy policies and the regulatory frameworks surrounding hydrogen-wind systems are provided. Subsequently, the main legal-administrative procedures and remaining barriers for the relevant applications are discussed. The final section is a summary discussion of legal-administrative drivers and barriers.

4.1 Methodology

The chapter draws on previous work in the HyLAW project (https://www.hylaw.eu/, [9]). HyLAW identified 70 legal-administrative procedures, for production, storage, transport and distribution, hydrogen as fuel and refuelling infrastructure, vehicles, electricity grid issues for electrolysers, gas grid issues, and stationary power. Each legal-administrative procedure was described in detail. The impact and severity of the identified barriers were nominally assessed, based on dialogue with stakeholders and other sources. The assessments were carried out separately for 18 European countries and later compared.

The main findings from HyLAW are available in an open database,[1] but the level of detail varies, and the main assessments were mostly carried out in 2017. A desk top study was therefore carried out specifically for this report. Google and Web of Science were used to search for recent policy documents and research literature, and reports from various stakeholders on:

- regulations, codes and standards – hydrogen, power-to-gas, power-to-X;
- non-technical barriers – hydrogen, power-to-gas, power-to-X;
- incentives and legal barriers – hydrogen, power-to-gas, power-to-X.

There are documents on the situation in general, as well as documents relating more specifically to the frameworks in Norway and Spain, from 2017 to 2019. The two countries were selected, since they are the national contexts for the three case studies in Haeolus, in Raggovidda, Smoela and Moncayuelo detailed in the D5.1 & D5.3 deliverables. Furthermore, key stakeholders with connection to the cases in Norway, including representatives of VarangerKraft Nett, VarangerKraft Hydrogen, Norsk Vindenergi Senter, the Norwegian Water Resources and Energy Directorate, and the Norwegian Directorate for Civil Protection, were consulted via phone/teleconferencing and emails.

4.2 Overarching climate and energy policies

The EU's long-term strategy *A Clean Planet for All* (COM (2018) 773) aims towards net-zero greenhouse gas emissions by 2050 and outlines a vision of the economic and societal transformations required to achieve this transition. By 2050, more than 80 % of the electricity in Europe will be from renewable energy sources. This will increase the potential for hydrogen-wind systems and the role of hydrogen as storage in the power sector, as well as for decarbonizing sectors that otherwise are difficult to electrify. The *Clean Energy for all Europeans package*, completed in 2019, consists of eight legislative

[1] https://www.hylaw.eu/.

items. As part of this package, the Commission adopted a legislative proposal for a recast of the Renewable Energy Directive. The RED II, or revised *Renewable Energy Directive – recast to 2030*, has raised the overall EU target for renewable energy sources consumption by 2030 to 32 % and added a transport sub-target, whereby fuel suppliers must supply a minimum of 14 % of the energy consumed in road and rail transport by 2030 as renewable energy. The directive also specifies national renewable energy targets, which has led all Member States (except Latvia) to provide subsidies for the deployment of renewable electricity.

The new *Electricity Directive (Directive (EU) 2019/944)* and the *Electricity Regulation (Regulation (EU) 2019/943)* aim to adapt the market to a system with more variable renewable energy, by attracting investments in energy storage and incentivising consumers to contribute actively to stability. Member States are also to incentivise distribution system operators to procure flexibility services, including storage services. Furthermore, the *Integrated Strategic Energy Technology Plan (SET-plan)*, which seeks to coordinate research and innovation activities in the EU and associated countries, includes hydrogen since 2014. Of a total of 1.34 billion euro granted from Horizon 2020 to energy storage on the grid and low-carbon mobility by the end of 2018, the largest share (37 %) was for hydrogen and fuel cell projects [7] [10].

In 2019, eight governments including that of Spain, launched an appeal to boost the Climate action by signing up to a specific Commission plan to achieve net-zero greenhouse gas emissions 'by 2050 at the latest'. The appeal proposes that the fight against climate change should be a cornerstone of the European Strategic Agenda 2019-2024. It also calls on the EU to raise its greenhouse gas reduction target for 2030. The eight governments emphasise that 'at least 25 %' of all EU spending should go to projects fighting climate change[2].

Spain's *draft Integrated National Plan for Energy and Climate (NECP 2021-2030)* proposes a reduction of 20-21 % of greenhouse gas emissions compared with 1990 levels. It plans to achieve up to 42 % consumption of renewable energies out of the total energy use, and a 74 % share of renewables in electricity generation by 2030. The total investments planned are 236 billion euro between 2021 and 2030, and the goal for 2050 is a 100 % renewable energy system. Spain is targeting nearly 27 GW of new wind capacity, thus targeting 50.3 GW of cumulative wind capacity to 2030. Of recent, there has been a row of applications for connection points for future renewable projects, sometimes without the corresponding capacity and where there is no infrastructure. Hydrogen is mentioned in the section on research, innovation and competitiveness, linked to flexibility and storage, but not defined as a main focus area. [11]

In Norway, the *Climate Act (LOV-2017-06-16-60)* defines legally binding targets for emission reductions. It states that Norway's climate gas emissions shall be reduced by 40 % by 2030, and by 85-90 % by 2050. The present government has agreed to increase the ambition level for climate gas reductions to 90-95 % by 2050 and cut 45 % of the emissions falling outside of the Emissions Trading System (ETS), including 50 % from the transport sector. The National action plan for green shipping, launched in June 2019, further specifies a target of 50 % reduction of emissions from local shipping by 2030. The 2016 *White Paper on Energy (Meld. St. 25 (2015–2016))* has market-based development of renewable energy as one of its focus areas and anticipates an increasing share of wind power towards

[2] https://www.euractiv.com/wp-content/uploads/sites/2/2019/05/Non-paper-Climate-FR-SE-PT-DK-LU-ES-NL-BE.pdf

2050. Industrial development and value creation based on profitable renewable resources is another focus area. Hydrogen is discussed as a possible energy carrier for the future, both for transport and stationary applications. Support for hydrogen refuelling stations is defined as part of the mandate of Enova, a parastatal for the promotion of sustainable energy solutions [12]. In the years since then (2016), there has been increasing focus on hydrogen in Norway, especially for road and sea transport, but also for future decarbonisation of the industry. An integrated, national hydrogen strategy is in progress and expected to be launched in 2020.[3]

Thus, overarching climate and energy policies are driving forces. However, neither Norway nor Spain have strong, integrated hydrogen strategies, nor a particular focus on hydrogen-wind systems. This underscores the importance of the Haeolus demonstration.

4.3 Overview, regulatory framework

The production and storage of hydrogen is impacted, at EU level, by three legislative acts: *the SEVESO Directive* (on the control of major accident hazards*), the ATEX Directive* (harmonising laws relating to equipment and protective systems for use in potentially explosive atmospheres) and *Directive 2010/75/EU on industrial emissions*.[4] These acts generate important obligations on operators involved in hydrogen production and handling, in terms of health and safety. The Strategic Environmental Assessment (SEA) *and* Environmental Impact Assessment *(EIA) Directives* apply indirectly; as production and storage of hydrogen fall within the categories production of chemicals and storage facilities for chemical products, they often require the development of an Environmental Impact Assessment (EIA), subject to national rules.

When it comes to electricity grid issues, *Directive (EU) 2019/944* establishes common rules for the generation (e.g. authorisation procedure for new capacity), transmission (e.g. unbundling, independence, etc.), distribution and supply of electricity, the organisation of access to the system, etc., together with consumer protection provisions. The 2012 *Energy Efficiency Directive (2012/27/EU)* lays down rules designed to remove barriers in the energy market and overcome market failures that impede efficiency in the supply and use of energy. Under the *Clean Energy for all Europeans package*, this directive was amended, with the most important change being the specification of an efficiency target for 2030 of at least 32.5 % [13]. Furthermore, commission *Regulation (EU) 2017/2195 of 23 November 2017* provides a guideline on electricity balancing, including the establishment of common principles for the procurement, activation and settlement of frequency reserves.

The transportation and distribution of hydrogen is subject to the existing rules for transport of dangerous goods within or between Member States. At European level the most relevant acts are *Directive 2008/68/EC on the inland transport of dangerous goods* and the UN agreements it is based on (*ADR, RID and AND*). For hydrogen as a fuel, the *Alternative Fuels Infrastructure Directive (AFID)* sets out minimum requirements for, amongst other, refuelling points for hydrogen. *Directive 2009/28/EC* sets mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy and for the share of energy from renewable sources in transport.

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[3] Announcement from the Norwegian Government: https://www.regjeringen.no/no/aktuelt/strategi-for-a-auke-bruk-og-produksjon-av-hydrogen/id2628730/. According to plan, the strategy would be launched by the end of 2019: https://sysla.no/snappet/regjeringen-skal-lage-hydrogenstrategi/.

[4] Full reference / links to all legal-administrative documents cited are provided in the Appendix.

The type-approval of motor vehicles is highly harmonised. Incentives for ownership of hydrogen vehicles are referenced by *Directive 2009/33 (Clean Vehicles) Directive* but varying from country to country. The rules and regulations applicable to boats and ships are generally established at international level, through the International Maritime Organization (IMO). The *Safety of Life at Sea (SOLAS) Convention* and *MARPOL (the International Convention for the Prevention of Pollution from Ships*) are particularly relevant. At EU level, *Directive 2014/90/EU on marine equipment; 2009/45/EC on safety rules and standards for passenger ships* and *2009/16/EC on port state control* are the most relevant legislative sources.

Injection of hydrogen into the gas grid for building heating is not relevant in Norway, but potentially a quite important application in many EU member countries. The *Gas Directive (2009/73/EC)* establishes common rules for the transmission, distribution, supply and storage of natural gas, as well other types of gas that can be injected into, the natural gas system. The Gas Directive was amended in 2019 to include a legal framework for gas pipelines to and from third countries. Part of the background are challenging negotiations with Russia about Nord Stream 2 and the amendment process therefore involved a certain level of debate [9], [14]. However, the aim is to ensure that all major gas pipelines entering EU territory comply with EU rules, are accessible to third parties, and are operated in an efficient and transparent way [15]. When it comes to stationary power (micro CHP's), *Regulation (EU) 2016/426* is the most significant act. It contains essential requirements concerning appliances burning gaseous fuels and their fittings and prescribes the obligations of manufacturers, importers and distributors when placing them on the market.

While HyLAW identified a number of challenges in terms of recognition as a zero-emission fuel, need for harmonisation and lack of specific guidelines, rules and standards, hydrogen as a chemical is for a large part regulated in the same way as for example LNG; as a dangerous, low-flashpoint substance. In the following section, the procedures, requirements and possible barriers for specific applications are discussed with some more detail.

4.4 Procedures and requirements for specific applications

4.4.1 Production

Permitting procedures for the establishment of hydrogen production in the EU do not distinguish between different energy sources and production technologies. Permits are linked to requirements regarding land use and general requirements for dangerous goods and low-flashpoint substances, where national legislation can be traced to EU Directives, especially:

- Risk Assessments (operationalised from the SEVESO Directive).
- Health and Safety requirements, conformity assessment procedures (the ATEX Directive).
- Integrated Environmental obligations (required by the IED).
- Environmental Impact Assessment procedures (envisioned by the SEA and EIA Directives).

In most countries, permits must be sought from different authorities (municipality, fire brigade, working environment and environment protection agencies). In a few countries the approval process has been delegated to a single, national authority [9]. In Norway, hydrogen is classified as an inflammable gas, category 2, and as such handled under the national *Regulation on handling of inflammable, reactive and pressurised substances and equipment and facilities used in the handling of such substances*. The municipality is in charge of the permitting process, which has three steps: (1) an initial general permit, (2) a permit to start construction, and (3) operation permit. The municipality works as a one-stop-shop and may involve other municipal, regional and national authorities as they see fit. When the facility will harbour 5 tons of hydrogen or more, special consent must be sought from the Directorate for Civil Protection (DSB), based on the national *Regulation to prevent major-accident hazards* and the SEVESO Directive. A detailed guideline regarding the application process and documentation requirements is available [16]. In some cases, a full environmental impact assessment (*konsekvensutredning*) may also be required.

In Spain, the prospective hydrogen producer must interact with several different authorities. According to the mapping in HyLAW, hydrogen production is not recognised as one installation but considered as a combination of chemical production and chemical storage site. The permitting process involves several different permits and authorities, in a total of eight steps.

An *Integrated Environmental Authorisation (AAI, Autorización Ambiental Integrada)* is also required. The procedure may be different for each Autonomous Region, but the authorisation should be equivalent. No minimum level of hydrogen production capacity is given. This means that all industrial hydrogen production facilities are considered on the same regulatory basis.

In Norway, the permitting procedure tends to be smooth, due to close dialogue between the business operators and municipalities. The procedures are relatively time-consuming and involve rather comprehensive risk assessments, but operators want to make thorough assessments also for their own sake and do not perceive this as a barrier. Obtaining a permit does not take longer than for other industrial facilities, less than one year. The cost of the required risk and safety assessments for a smaller facility, like the pilot plant at Raggovidda, is in the range of or 25 000 €.[5] In Spain, the permitting process is rated as a medium severity level barrier. This is related to the lack of specific legislation for hydrogen, and that permits must be obtained from different authorities on local and regional level.

Since 1951 the Norwegian government has charged a special tax fee on electricity (*elavgift)*, to encourage energy efficiency. However, power-intensive industry, including electrolysis, has enjoyed a significantly reduced fee. From 2019 the state electricity fee has been removed completely for electrolysis, as well as for chemical reduction, metallurgical and mineralogical processes. This is clearly a conducive factor, and part of the rationale behind the removal is precisely to facilitate hydrogen production.

4.4.2 Storage

The permitting procedures for storage of hydrogen are, as in the case of hydrogen production, related to land use planning and general requirements in terms of e.g. risk assessment, safety requirements and environmental assessment. In both Spain and Norway, municipalities have the responsibility to approve the land use plans. The procedures for approval are not different from the procedures for storage of other inflammable gases. The same is the case for approval of the storing facilities. In Spain, the regional government has the responsibility for the permitting process.

In Norway, the threshold is 5 tons. Below this limit the applicants may apply for general permission, construction and operation permits directly from the relevant municipality. Installations harbouring more than 5 tons require application for special consent from the Directorate for Civil Protection, according to the *Control of Major Accident Hazards Involving Dangerous Substances Regulation, 2016*,

[5] 250 000 NOK with the conversion factor 0.1 €/NOK

which implements the SEVESO directive in Norway. The specific requirements, including risk assessments, zoning, equipment, civil protection, monitoring and risk-prevention measures, reporting duty and requirements of consent from neighbouring enterprises, , are listed in a special *Guideline for storage of dangerous substances* [17]. In Norway, the procedure is not associated with any significant barrier. In Spain, storage is regulated under the *Royal Decree 656/2017 – Regulation of Storage of Chemical Products and its Complementary Technical Instructions.* The stakeholders consulted in HyLaw saw this as a medium severity barrier and called for a regulation that specifies thresholds for domestic use, moderate but not industrial storage, and massive industrial storage. The background is that, for example in Aragon, all commercial hydrogen storage is considered as industrial and therefore requiring either a simplified or a full EIA.

4.4.3 Connection to E-grids

There is no specific regulation for electrolyser connection neither in Spain nor Norway, so the procedure according to regulation is the same as for other connecting consumer facilities. In Norway there are several different regulations to comply with, including the *Regulation on quality of electrical energy in the Norwegian Electricity Grid*, *Regulation on electrical low voltage installations*, and the *Regulation on preventive security and contingency in energy supply*. In Spain the connection procedure is regulated by a *Descriptive guide to the Grid connection procedure*, with reference to a resolution by the General Secretariat for Energy. Applicants must follow the same procedure as for other loads. This mainly consists on obtaining the access permit, and connection permit. The permitting body in Spain depends on the voltage level. If the connection is in high- or Medium-voltage, the TSO Red Eléctrica de España (REE) is the authority. If the connection is in the Low Voltage side, the DSO is the authority to approve it.

In Norway, the Norwegian Water Resources and Energy Directorate (NVE) has the overall authority, whereas Statnett SF has the role of Transmission System Operator (TSO). Under the current Norwegian regulation, Statnett approves the technical design of generators, network units and industry connections, before units may connect to the transmission and higher voltage distribution grids.

If the connection is done at distribution level, the local DSO is in charge of the permitting process. Until 2019 network companies were to decide a connection charge to cover the costs of connecting new customers to the network or to cover the costs of reinforcing the network for existing customers. The *Norwegian Energy Act* states that any entity engaged in physical trading, generation and/or distribution of electric energy in Norway is required to hold a trading license (from NVE). For all new projects (wind-, gas – and hydro power plants, power lines, transformers) a license to build and operate must be granted. NVE considers the economy, public and private interests and environmental issues for every project.

NVE further regulates the distribution system operators (DSOs) and Statnett using an incentive-based revenue cap (RC) model. All network companies are responsible for determining tariffs within their income cap according to the regulation of the tariff structure. Network companies shall offer non-discriminatory tariffs and conditions. Any differentiation must be based on network related criteria that are objective and verifiable, giving price signals about effective utilisation and development of the network.

Consumers in the distribution network are charged a fixed component that covers customer-specific costs and a share of the other fixed costs in the network. Tariffs for production are independent of the recipient of the power. As for other tariffs, the tariffs for production consist of an energy component and a fixed component. The fixed component for 2018 was 0.0013 €/kWh.[6] Prosumers feeding in less than 100 kW are not charged the fixed component for production. There is less detailed information for Spain available, but according to HyLAW the procedures are rated as 'neutral' and no information suggesting that there are specific barriers to hydrogen production in this area were found. In Norway, the future regulation of grid tariffs will have an impact on hydrogen production costs in cases where the plant requires grid connection. This would for example be the case in one of the two alternatives considered in Smøla, where the plant would be located closer to the point of use than to the windfarm, to reduce transportation costs. In such cases, possible increase of grid tariffs may represent a barrier to implementation of the project.

In Spain, Royal Decree 1955/2000, as amended by the Electricity Act 24/2013, regulates the regime applicable to transportation, distribution, commercialisation and supply activities. Three kinds of permits are required; authorisation of a draft technical installation document, subsequent project implementation approval, and final operating authorisation allowing energy to be transmitted to the facilities for commercial exploitation [18]. Royal Decree 900/2015 regulates the supply and generation of electricity for self-consumption. It stipulates the tolls and charges payable, according to the principle that self-consumption must contribute to financing the costs and services of the system to the same extent as other consumers (criticised as 'tax on the sun'). There is a fixed cost according to installed power capacity and a variable cost according to the electricity self-consumed. The regulation also considers a specific surcharge for those who use batteries to store some of the electricity produced (exempted are consumers on islands and those with no more than 10 kW capacity). Facilities with a capacity generation higher than 100 kW may charge for the excess energy that they feed into the grid, at the current wholesale market price. They are, however, subject to power generation charges as well as a 7 % tax on energy production.

The responsibility for setting regulated electricity and gas network tariffs has been handed to an existing independent regulatory authority, the National Commission on Markets and Competition (CNMC). This happened through *Royal Decree-Law 1/2019, of 11 January*, which brings the powers of the CNMC in line with those established in Directives 2009/72/CE and 2009/73/CE [19]. CNMC may inspect and sanction all types of infractions provided for in the electricity sector legislation.

4.4.4 Distribution

Transport of hydrogen in the EU is regulated by *Directive 2008/68/EC, on the inland transport of dangerous goods*, which applies to the transport of dangerous goods by road, rail or inland waterways. Transport by road is further regulated by *ADR European Agreement concerning the international carriage of dangerous goods by roads*. The *Transportable Pressure Equipment Directive (TPED) (Directive 2010/35/EU)* applies to the design, manufacture, and conformity assessment of transportable cylinders, tubes, cryogenic vessels and tanks for transporting gases such as hydrogen. It also covers their associated valves and other pressure equipment. There are no specific requirements on national level for transportation of hydrogen, in terms of roads, specific routes, and vehicles neither in Norway nor Spain. The approval processes are similar to those for other class 2 gases. In Norway, the Directorate for Civil Protection (DSB) is responsible for the *Regulation of road transport of dangerous goods* and the *ADR/RID regulation*, while the Norwegian Public Roads Authority is responsible for ADR driver and vehicle certification and control. In Spain, the Directorate General for

[6] 0.013 NOK/kWh with the conversion factor 0.1 €/NOK

Road Transport (Dirección General del Transporte Terrestre, 'DGTT') and the Directorate-General for Traffic (Dirección General de Tráfico, 'DGT'), are the organisations in charge [20].

Transport of hydrogen on board ships is regulated under the *International Maritime Dangerous Goods (IMDG) Code* and the *International Gas Carrier (IGC) Code (IMO MSC 5(48)),* which both are written in conjunction with the *International Convention for the Safety of Life at Sea (SOLAS)* and the *International Convention for the Prevention of Pollution from Ships (MARPOL 73/78)*. The IMDG Code gives requirements for compressed and liquid hydrogen which are comparable to those for compressed and liquid natural gas, and they have the same limitations as packed cargo. The latest version, implemented from 2019-2020, specifies requirements for a new IMO type 9 tank for road gas elements vehicles for the transport of compressed gases of class 2 [21]. Such tanks must be approved by the competent authority for road transport as well as the authority for sea transport, which must certify their compliance to the design, construction and equipment provisions of IMDG Code. This has implications for operators aiming to transport hydrogen via trucks and routes involving ferry transfers.

The IGC Code lacks specific requirements for hydrogen. A set of interim recommendations for carriage of liquefied hydrogen in bulk was adopted by the IMO (resolution MSC.420(97), on 25 November 2016). Their application is so far limited to a pilot project where Kawasaki Heavy Industries Ltd got Approval in Principle (AiP) from ClassNK. Whereas storage of fuel natural gas is allowed on-board passenger ships carrying more than 25 passengers, it is anticipated that initial restrictions regarding storage quantities and locations will be put in place for hydrogen (e.g. storage on top deck). Thus, there is a regulatory gap and some level of uncertainty, both when it comes to gaseous and liquid hydrogen. In Norway, the relevant IMO regulations are enshrined in national regulations, first and foremost the *Regulation on maritime transport of dangerous goods.* Likewise, Spanish shipping law, mainly regulated by the *Act 14/2014 of 24 July on Maritime Navigation (the Maritime Navigation Law or MNL)*, aims for uniformity between international conventions and domestic legislation [22].

Pipeline systems for distribution of hydrogen already exist in some countries, such as the U.S. In Norway, such pipelines would be regulated the same way as pipelines for natural gas, under the *Regulation on handling of inflammable, reactive and pressurised substances and equipment and facilities used in the handling of such substances*. A special *Guideline for the transport and distribution of petroleum in onshore pipelines* specifies the requirements and procedures for class 2 gases, including hydrogen. In theory, a blend of up to 20 % hydrogen in natural gas can also be transported without modifying natural gas pipelines [23]. Modifying the same pipelines to carry pure hydrogen, however, requires addressing a number of issues, including the potential for embrittlement and sealing difficulties at fittings that are tight enough to prevent natural gas from escaping, but possibly not hydrogen. In Norway, these issues are currently addressed in the HYLINE project.[7] While so far associated mainly with hydrogen from natural gas reforming with CCS, this mode of distribution may also be relevant for hydrogen from on- or offshore wind in future.

4.4.5 Injection into gas grid

Injecting hydrogen into natural gas grids for heating is not very relevant within Norway, which only has one small, local gas grid in Rogaland county. Spain has extensive gas infrastructure, including 87 699 km of pipelines. According to recent news reports there is a considerable over-capacity and fear of

[7] https://www.sintef.no/en/projects/hyline-safe-pipelines-for-hydrogen-transport/

lock-in effects associated with further grid investments.[8] Green hydrogen could be one solution contributing to a future 'greening' of the gas grid, and/or reducing the risk of over-investment by facilitating local storage and use of renewable energy. In Norway, several actors see a potential for future export of green as well as blue hydrogen to help decarbonise building and industry heating in other parts of Europe.

As noted above, the *Gas Directive (Directive 2009/73/EC)* constitutes the overall regulatory framework for hydrogen injection into the gas grid within the EU. However, the regulatory framework has been drawn up around natural gas, with quality standards based on gas calorific value. Adding hydrogen to the gas stream may impact on this value, as well as on the flow properties, density and flame speed, with further impact on pipeline materials and gas grid operations. There is no specific regulation for hydrogen injection at EU level. The volumes of hydrogen allowed are very small and varying across countries, as shown in the table below [9]. Still, an overview article by Quarton and Samsatli lists 25 power-to-gas projects including hydrogen injection to the gas grid that have been completed or are operational or planned since 2007 [24].

Table 1: Levels of hydrogen accepted for injection in the gas grid in selected EU countries [9].

Legal framework 'Acceptable' H_2 level (typically mandated by legislation	**Countries**
'Minimal' H_2 concentration at **0.1 to 0.5 vol%** (reflecting typical background concentrations in natural gas)	**IT, LV; SE, UK**
'Low' H_2 concentration at **1.0 to 4.0 vol%**	**FI, AT**
'Mid' H_2 concentration at **6.0 vol%**	**FR**
'High' H_2 concentration at **up to 10.0 vol%**. The applicable H_2 threshold may fall below this, depending on down-stream consumers H_2 tolerance and other fac-tors (e.g. underground storages, large scale gas turbines, vehicle CNG cylinders type 1/CNG refueling stations	**DE**
No formal H_2 concentration rules but based on safety limits with reference to natural gas operations	**BE, BG, DK, ES**

In Spain, Article 54 from *Law 34/1998, on the hydrocarbons sector*, states that hydrogen is permitted only when it is injected with SNG. This constitutes a severe barrier. Largescale, flexible use of hydrogen in the gas grid would require harmonisation, and to allow higher concentrations it would be necessary to revise the overriding EU regulations [25].

4.4.6 Road transport

Type approvals and permits related to the use of hydrogen vehicles in road transport are regulated by common EU legislation. In terms of type approval, the vehicle has to be approved in accordance with *Directive 2007/46/EC* and *Regulation 79/2009*, and the manufacturer has to apply for it. The

[8] https://www.euractiv.com/section/climate-environment/news/spains-luxurious-gas-infrastructure-under-the-spotlight/

requirements and periodic testing /inspection required are based on common EU directives, and they are the same for hydrogen cars as for other cars.

In Norway, hydrogen fuel cell vehicles are recognised as zero-emission vehicles, the same way as battery-electric vehicles. Type approval is carried out by The Directorate of Public Roads. Individual vehicle registration is handled by The Norwegian Public Roads Administration, and technical inspection is carried out The Norwegian Public Roads Administration through their regional traffic offices. Norway has one of the best incentive schemes for hydrogen and battery-electric cars in Europe [9]. Both categories are exempted from VAT, which is 25 % for other cars. Hydrogen cars are also exempted from the non-recurrent registration fee, which is a sizeable incentive. From 01.01.2018, the system of annual fees was replaced by a system of traffic insurance fees payable to the state (counted per day). Both hydrogen and electrical cars and heavy-duty vehicles are exempted. While the government made a resolution in 2017, that electrical cars may be charged up to 50 % for parking, in road toll and on local ferries, hydrogen cars are still exempted from road toll. Municipalities may choose whether to charge low emission vehicles for parking in public spaces or not. However, low emission cars can maximally be charged 50 % of the normal fee. Among the climate goals of the present government, it is stated that by 2025, 100 % of the sale of new cars in Norway shall be zero-emission cars.

In Spain, the Ministry of Economy, Industry and Competitiveness is responsible for the type approval, while The Dirección General de Tráfico (The General Directorate of Traffic) handles registrations. The technical inspection body is Inspección Técnica Vehicular. Hydrogen fuel cell electric vehicles are registered as zero-emission cars. The 2019 *Funding programme for efficient and sustainable mobility (MOVES Program)*, includes a scheme where both private and professional buyers may receive aid when purchasing fuel cell electric vehicles and other low-emission vehicles. The specified amounts for a hydrogen passenger car are 5 500 €, for both private persons and professionals, while for heavy trucks, buses and vans the amount is 15 000 € [26]. Policies for the uptake of zero- and low-emission cars are also found at regional and local level, as part of local mobility strategies [27]. According to the National plan for alternative fuels infrastructure, Spain aims to have 500 hydrogen fuel cell vehicles by 2020.

The interest in Green public procurement (GPP) as a sustainable development tool has increased significantly in recent years. In Norway, GPP [28] is used actively to promote zero emission transport solutions, including hydrogen fuel cell vehicles. The current *Public Procurement Act*, in force from 01.01 2017, requires the procuring agent to consider environmental aspects carefully and specify environmental requirements where relevant. The *Regulation on Public Procurement (Forskrift om offentlige anskaffelser)*, states that where environmental impact is used as a criterion it should be weighted minimum 30 %. While there is a principle of technology neutrality, GPP is increasingly used to facilitate zero-emission transport solutions. Some counties and municipalities, most notably Oslo and Akershus, have used GPP to facilitate uptake of hydrogen buses and fleet vehicles, and there are ongoing public-private partnerships for fleet collaboration to reduce the risk associated with first-generation heavy vehicles in several other counties. For Spain less detailed information was found, but the use of GPP seems to have been more limited so far [29].

In Norway, hydrogen is classified as a zero-emission fuel, but there is no binding or voluntary, uniform certification of origin system at European level and divergent approaches may jeopardise the free movement of (green) hydrogen across borders. This is also considered as a barrier in Spain. However, the EU CertifHy project [30] has developed a guarantee of origin (GO) scheme that covers either hydrogen produced from renewable energy (bio, hydro, wind and solar) - defined as 'Green Hydrogen' - or from non-renewable low carbon energy sources (nuclear, fossil with CCS) - defined as 'Low Carbon Hydrogen'. In both cases the greenhouse gas (GHG) intensity of the hydrogen considering the whole production pathway ('well-to-gate') is below a set threshold (min. 60 % below the production of hydrogen from natural gas). Purity requirements are defined by the ISO 14687–2 and SAE J2719_201511 international standards [31]. *Directive 2014/94/EU* states that the ISO 14687 standard shall be followed, and this procedure is therefore not associated with any significant barrier.

When it comes to hydrogen refuelling stations (HRS), the rules in terms of land use planning do not differ significantly from those of conventional refuelling stations (in general) and those using compressed natural gas (CNG) in particular. As regards permitting requirements, HRSs in Norway are subject to the same requirements as conventional fuel and natural gas stations, all over the country. However, in Spain the process depends on each autonomous community and may therefore vary from one autonomous region to the other. Furthermore, on-site production of hydrogen would result in the HRS being classified as an industrial activity, and hence only being permitted in an industrial zone, significantly limiting the business case for development of HRSs with on-site production. A finding from HyLAW is that this may be due to lack of clarity on the scope of the EIA, SEA, IED and SEVESO Directives, related to the historical assumption that production of hydrogen is a chemical process involving direct emissions and the interpretation of 'production of hydrogen on an industrial scale'.

In Norway, the application procedure and permitting requirements are the same as for production or storage facilities. The municipality is in charge for all the steps. The procedure is straightforward, but in practice the time it takes may vary from 6-7 weeks and up to 2-3 years, depending on the level of dialogue with the municipality and other local stakeholders. Under the Planning and Building Act and the Fire Prevention Act, the *Regulation on handling of inflammable, reactive and pressurised substances and equipment and facilities used in the handling of such substances*, and the *Regulation of pressurised equipment and requirements of conformity assessment* are most central. There is a national *Guideline for tapping of dangerous substances*, which lists specific norms and requirements for inflammable substances and states that HRS should be designed according to *ISO/TS 20100 Gaseous hydrogen – Fuelling stations.*

In Spain, the *Royal Decree 639/2016* establishes a framework for the implementation of infrastructure for alternative fuels and states that new HRS must conform the quality characteristics of *ISO 14687–2.* A main concern is that certification of impurities is very restrictive and there are no laboratories able to certify the quality of hydrogen as fuel. The application for permission to establish and operate a HRS should be very similar to the applications to establish conventional fuel stations, but most regions have no precedent of HRS, and therefore there is no guarantee of a uniform process. There is not a specific procedure for opening a HRS as this facility is not recognised itself. As there is no dedicated regulation for HRS it has to be considered as a combination of production, storage and public sales of hydrogen and the resulting process is very complex.

Spain currently has 6 HRS, and according to the *National Action Framework for the development of the market and the infrastructures for alternative fuels in the transport sector (MAN)* [32], and 20 publicly accessible hydrogen refuelling points are foreseen by 2020. The plan contains an extensive list of measures, most already in place [33]. Norway has 5 HRS. At the time of writing all are closed due to an HRS explosion in the summer of 2019 but scheduled to reopen following third party examination and double-check that they meet the documentation requirements. Presently there is a national support scheme providing grants for up to 3 HRS per year. The national hydrogen association has stated the need for a basis network of 20 HRS by 2023. The *Norwegian Action plan for infrastructure for alternative fuels in transport,* which came out in 2019, states that the support will be continued but depending on the increase in number of vehicles and with a stronger focus on solutions for heavy-duty transport.

4.4.7 Maritime transport

In Norway, greener shipping is a national priority area [34]. A number of measures, such as reduced electricity fees for ships in business activity, a lending scheme for condemnation and renewal of the local shipping fleet, a grant scheme for climate and environmentally oriented public procurement processes and increased funds for research into climate-friendly shipping have been introduced. Norway has also been working through the International Maritime Organization (IMO), to define an initial, international strategy on the reduction of greenhouse gas emissions from ships. Launched in April 2018, this initial strategy envisages a reduction of total annual GHG emissions by at least 50 % by 2050 [35].

A resolution by the Parliament in June 2016 encourages the use of development contracts for hydrogen ferries, and the Government's recent ban of any kind of carbon emissions in the waters of the UNESCO World Heritage sites Nærøyfjorden and Geirangerfjorden from 2026 is another important step.

Design or type approval is the most substantial legal-administrative requirement for ships. The International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) is the overarching legal framework. The code is ratified in Spain, where *Directive 2014/90/EU on marine equipment* and *Directive 2009/45 on safety rules and standards for passenger ships* transpose the overarching IMO conventions, but there is limited experience. In Norway, the national *Regulation of ships using fuel with flashpoint below 60°C* makes the IGF Code mandatory for new constructions or reconstructions. It contains detail requirements for natural gas as fuel only, and internal combustion engines, boilers and gas turbines. Continued work has been agreed under the IGF Code working group, but the use of fuel cells is presently not regulated. Due to this regulatory gap, approval must be sought through the Alternative Design approach, as defined in *MSC.1/Circ.1455 – guidelines for the approval of alternatives and equivalents.* This is a costly and time-consuming process, including comprehensive technical, risk and environmental assessment, as well as broad stakeholder involvement. It is estimated that the procedure takes at least one extra year, as compared to gaining final approval for conventional ships. On top of this, there is the need for technology qualification and development of standards.

When it comes to ship registration there are no specific requirements for hydrogen-powered ships. Additional documentation requirements may come in, but once the design has been approved, no major barriers are foreseen. The additional documentation requirements for alternative designs may also be followed by specific operation and maintenance requirements, but due to lack of experience it is difficult to assess what the time and cost implications could be.

Onshore landing and bunkering installations for hydrogen fall under the same legislation as onshore landing and bunkering facilities for of other inflammable gases, that is the *SEVESO and ATEX Directives*, as well as the *Pressure Equipment Directive (Directive 2014/68/EU)*. In Norway, the national *Regulation for safe handling of inflammable, explosive and pressurised substances, including relevant installations and equipment* and the *Guideline for tapping of dangerous substances*, which includes a special chapter on bunkering stations for LNG, are the key documents. While there previously was a threshold of 5 tons, all bunkering installations for hydrogen now require special consent from the Directorate for Civil Protection, whether they serve passenger ships or not. Applying for special consent from the Directorate for Civil Protection is a time-consuming process. The normal processing time is 3 months, including a 4-week hearing period, but the procedure may also take considerably longer, if revisions are needed. A comprehensive, quantitative risk assessment is required for approval, and this is often outsourced to a consultant. The costs depend on case and are difficult to specify. The bunkering must be overseen by qualified personnel, and the rules regarding the location of passengers and personnel during the bunkering process must be clarified. This adds further uncertainty to technological innovation projects, which are financially risky at the outset.

As the legislation in this area is function-based rather than providing detail regulation, new procedures for hydrogen installations may not be needed. However, there is the need for close assessment and consideration of specific guidelines. Current procedures for bunkering of LNG and the experience from HRS for cars provide a first knowledge basis, but further risk studies and technology qualification is needed, both for liquid and compressed gaseous hydrogen. All pressurised components, such as tanks, piping and equipment, must be in compliance with the *EU Pressure Equipment Directive (97/23)*. In other words, there is an operational barrier and need for more specific guidelines for onshore landing and bunkering installations. The lack of detail regulation is supplemented by comprehensive assessment requirements, which can be quite challenging for economic operators, at this early stage in the development.

In both Norway and Spain, the national maritime authorities represent centralised approval/permitting bodies. Much of the assessment and control work, depended on the vessel types, is delegated to selected classification companies by the maritime authorities. The IGF Code makes it possible for the applicant to obtain approval from the maritime authorities by documenting that hydrogen operation can be designed to be just as safe as conventional vessels. Overall, the barrier severity level is rated as high, both for Norway for Spain. In Norway, the Public Roads Administration has offered an innovation development contract with shipping companies in order to develop hydrogen ferries, and several counties are working towards similar initiatives, where regulatory challenges as well as technical and financial issues are addressed. The Maritime Authority and Directorate for Civil Protection are also involved as partners in several research and development projects.

4.4.8 Stationary power (injection of electricity)

HyLAW found no common EU framework for connection of stationary fuel cells to the electricity grids. For power generating units connecting to the grid in general, the conclusion of a connection (injection) agreement with the local/ regional electricity network operator is required. In some countries it is necessary to submit quite extensive technical documentation and even to carry out a feasibility study, which may cause additional costs and delays. The time needed for signing of a grid connection agreement varies widely and may take up to six months. Although this is not seen as a significant operational or economic barrier, there is a need to simplify the administrative procedures and to reduce and adapt the required technical documentation and possible preliminary studies.

In Norway, any self-production requires that the installation shall be connected to the grid and operated under an agreement (Plusskunde-avtale) with the DSO. In principle, the fuel cell micro CHP, based on renewable sources, is facilitated through available self-production agreements and support to cover up to 30 % of the total installation costs. No additional equipment requirements have been set for fuel cell micro CHP. This is also not foreseen by the consulted stakeholders. For self-production in general a metering system for both buying and selling must be installed by the DSO or a licenced electrician approved by the DSO.

There is an ongoing process to implement the *Clean Energy Package*, and the EU *Guidelines for System Operations and Energy Balancing*. As per now the prices for balancing services, including frequency containment reserves (FCR) are too low to be of interest for many potential actors, and there are practical challenges to the inclusion of use and aggregated loads, such as geographical distribution and bottleneck issues for aggregated bids. The latest version of the roadmap towards a Nordic Balancing Model aims to implement a Single Price Model by Q2 2021, together with the implementation of automatic frequency restoration reserves (aFRR) and manual frequency restoration reserves (mFRR) capacity markets, mFRR energy activation markets and 15 min time resolution. The aim is to have the new model in place by 2024 [36].

In Spain, the *Royal Decree 244/2019, of 5 April*, regulates the administrative, technical and economic conditions for the self-consumption of electricity. The regulation defines self-consumption as *'the consumption by one or more consumers of electrical energy coming from generation installations close to and associated with consumption installations'*. Thus, several consumers will be able to join the same generation installation, and unlike previously, a self-consumption facility may be located in more than one dwelling. When there is a supply with self-consumption with surpluses, i.e. possible to inject surplus energy into the transport and distribution networks, the installation may voluntarily benefit from a surplus compensation mechanism as long as they comply with certain conditions. At the same time, self-consumed energy of renewable origin, cogeneration and waste is exempt from all types of charges and tolls. Beside access permit and connection point, the operator must have the necessary measuring equipment which, in general, will be a two-way measuring equipment at the border point or a measuring equipment at each of the border points [37].

4.4.9 Decarbonisation of existing industry

Hydrogen can replace coal, oil and gas as a fuel in some industrial processes, reducing on-site emissions. While steam methane reforming ('grey' hydrogen) can be substantially decarbonised by adding carbon capture, utilisation and storage (CCUS), 'blue' hydrogen, electrolysis based on wind power may provide a zero-emission alternative. According to a recent study by ICEF, blue hydrogen would add modest costs to production of hydrogen and raw industrial products. Green hydrogen would add more substantial costs, but as costs for firm renewable power decrease, green hydrogen may become more attractive [38].

While power-to-gas is associated first and foremost with decarbonizing building heat and power in many EU countries, the potential for decarbonisation of industry is strong in Norway, given that the power sector largely is renewable already. Generally, emissions from industry are regulated under *Directive 2010/75/EC on Industrial Emissions (IED)*, which aims to prevent and reduce harmful industrial emissions while promoting the use of techniques that reduce pollutant emissions and that are energy and resource efficient. In Norway IED is implemented through the *Regulation to control pollution*, last amended in 2016. Measures to reduce greenhouse gas emissions are encouraged through a CO_2 tax, which is increased by 5 % in the national budget for 2020 and will continue to increase significantly towards 2025. There are also negotiations surrounding a CO_2 fund for the industry, where CO_2 taxes payable would be ploughed back into emission reduction measures.

Furthermore, the state funding agency Enova offers support for energy efficiency and CO_2 reducing measures in industry, but not for implementation of already mature technologies. Support may thus be granted for innovative concepts including green hydrogen produced from wind power, but not merely for the installation of an electrolyser. Public support may also be sought through Pilot-E, a special funding scheme for largescale demonstrations with identified end-users. In 2019, Nel and Yara were granted support for a project to develop and implement a new generation alkaline electrolyser, tailormade for large-scale ammonia production and other industrial applications.[9] Together with the pilot studies carried out at the titanium and iron ilmenite producer TiZir,[10] this may pave the way for wider application of hydrogen for industry decarbonisation. A recent review of power-to-gas projects in Europe, found 17 projects focusing on hydrogen for industry [39].

Production and use of hydrogen to fuel processes in industry are already regulated, under the *Regulation for safe handling of inflammable, explosive and pressurised substances, including relevant installations and equipment* and the *Regulation of pressurised equipment and requirements of conformity assessment*. However, large parts of the industry are based on fossil technologies, where changing to hydrogen and renewable sources may require radical and costly process changes.

According to a recent review, recent government policy on climate in Spain [40] includes the preparation of a roadmap to reduce GHG emissions in several industry sectors, as well developing a national Carbon Fund to increase the number of national initiatives to help reduce GHG emissions. In 2018, 19 % of the national GHG emissions stemmed from industrial activities. There is a national Tax on Greenhouse Gases, implemented through *Law 16/2013*, which taxes the sale and use of gases used in industry and in heating facilities that have negative effects for global warming. There is also 'green cent' levy on the sale of gas, coal and fuel-oil and gas-oil, and certain other taxes that may have an environmental approach, such as a tax on sale of electricity [41]. Here too hydrogen is regulated already, as an industrial chemical.

4.4.10 Sector coupling

Sector coupling, or the development and valuation of synergies between different parts of the energy system, is gaining more and more attention in the EU. End-use sector coupling is especially relevant for building heating and industrial processes, where electrification alone is challenging, and as noted above, hydrogen fuel cell is a promising technology. Cross-vector integration, i.e. integrated use of infrastructures and vectors, such as electricity, heat and gas, is a key to increased flexibility [42]. Amongst other, this has led to an increasing focus on integrated user cases and holistic solutions, such as in the concept of Hydrogen Valleys, which are projected both in Spain and Norway.[11] A recent study for the EU argues that current energy market designs form a barrier by not internalising all externalities of low-carbon and carbon-intensive technologies, and by impeding the participation of sector coupling technologies. This is in line with some of our observations above. The study argues for more integrated energy system planning and operation, as well as facilitation of high-risk innovations [42].

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[9] https://www.yara.com/news-and-media/news/archive/2019/yara-and-nel-carbon-free-hydrogen-for-fertilizer-production/

[10] https://www.ntnu.edu/documents/1263635097/1271002173/06-HaraldGrande_Prereduction+and+use+of+Hydrogen+at+TiZir.pdf/ba04bca2-ff14-4819-82b1-c8e3dbf89829

[11] https://s3platform.jrc.ec.europa.eu/hydrogen-valleys

4.5 Discussion, legal-administrative drivers and barriers

The overview of procedures and requirements shows that hydrogen for a large part is regulated as an industrial chemical, together with other inflammable low-flashpoint gases. This implies that hydrogen production integrated with wind power generation in itself does not require new regulations, and that many of the applications considered in Haeolus, likewise, can take place within the framework of existing regulations, codes and standards.

On the other hand, the construction of hydrogen as an industrial chemical also has some unfavourable implications, in that electrolysis, which only has pure water and oxygen as by-products, is juxtaposed with other forms of chemical production, which may have adverse environmental impacts. In the case of Spain and several other EU countries, this has the implication that an environmental impact assessment is required once the production or application is at a commercial scale. It is also associated with operational barriers, in that hydrogen production at the outset is associated with industrial zones and it may be more complicated to gain approval for activities involving hydrogen production outside such areas, be it HRS with on-site small-scale production, or possibly, largescale production in peripheral windy areas without designation as industrial parks.

In Norway, a formal EIA is usually not required, unless the facility is located close to and/or suspected to impact on an environment protected area; considered to threaten biodiversity and endangered species; and/or falling under the *Regulation to prevent major-accident hazards* and the *SEVESO Directive.* Here too, the permitting procedure may be smoother for activity within a predefined industrial area, but the observation from HyLAW is that there usually is an individual assessment and close dialogue between operators and the relevant authorities, leading to relatively flexible and smooth processes, also for non-industrial areas.

The CertifHy scheme is an important step to build acceptance for hydrogen as a low-emission fuel, and several stakeholders suggest the scheme should be adopted by public decision-makers. The need to develop harmonised rules on guarantees of origin which take account of the need for seasonal storage is also emphasised in previous research [43]. Key stakeholders further call for norms and standards in other areas, for example when it comes to HRS design and lay-out. On the other hand, the relevant authorities and other stakeholders contend that many risk and safety requirements are better function-based. The need to build social acceptance for the deployment of hydrogen and related infrastructure as safe technologies is also noted in other studies [1], [44].

Another challenge is that certain procedures, such as the permitting process for establishment of hydrogen production in Spain, are rather complex, involving many steps and relating to several authorities at local, regional, and national level. This, according to HyLAW, would be the same in many other EU countries, whereas other countries, including Norway, have a one-stop shop at one administrative level. On the other hand, Spain has a *Descriptive guide to the Grid connection procedure*, which applies also for connecting electrolysers to the grid, whereas Norwegian actors must relate to several different regulations and requirements. Complex procedures among involved authorities and limited information and assistance to applicants have been identified as main, non-economic barriers [44].

The need for harmonisation across regions and countries is also apparent. When it comes to permitting procedures there are local variations in both Spain and Norway, which may create unpredictability, delays and added costs for economic operators. However, these are mainly operational barriers. A more critical factor when it comes to largescale deployment is the lack of harmonisation as regards accepted injection levels in the European gas grid. This was one of the key messages from HyLAW and is also emphasised in Hydrogen Roadmap Europe [1], which recommends that regulators and gas companies should implement binding targets for renewable content in the gas grid, and/or other instruments such as contracts-for-difference, feed-in tariffs or investment supports. A most apparent regulatory gap is found in the lack of specific requirements for design/type approval of hydrogen ships [35]. These are in principle regulated under the IGF Code. The lack of specific requirements necessitates application of the Alternative Design procedure, which involves added costs and obligations on the side of operators. On the other hand, technology development is still at an early stage. While working to address the gap through the IMO, key stakeholders hold that it may be counterproductive to define specific requirements too soon. While some claim there is a lack of regulation also when it comes to onshore bunkering facilities, the Norwegian Directorate for Civil Protection states that relevant regulations exist, but there may be the need to develop specific guidelines and standards for hydrogen. Norwegian authorities have decided to take a special responsibility in this area, as part of the recently established *Action plan for green shipping* [45].

There are also remaining gaps when it comes to connecting stationary fuel cells to electricity grids for the provision of flexibility services. Under the *Clean Energy Package*, Spain has developed a new regulation that takes new and more complex patterns of prosumption into account but does not specifically consider hydrogen fuel cells. Norway and the other Nordic countries have established the Nordic Balancing Model (NBM) to improve balancing market efficiency, while maintaining operational security. This is a complex, five-year program where several great challenges remain to be resolved, including changing and automating critical system operation processes.

Predictable framework conditions are important. However, the main barriers to largescale impact of hydrogen-wind systems on sustainable energy transition in Europe are economic. As noted, both Spain and Norway have long-term climate and energy strategies that involve considerable increases in wind power generation and an associated growth in demand for flexibility. However, the situation presently is characterised by a chicken-or-the-egg dilemma. While hydrogen fuel cell cars are available, there is a lack of public knowledge and awareness of hydrogen as an option for sustainable mobility. In the EU, only 14 member states have included hydrogen in their *National plans for alternative fuels infrastructure*, and the government initiatives for increasing the transmission and distribution (T&D) networks and use of hydrogen vehicles are limited [44]. According to the European Court of Auditors (ECA) [10], as well as Hydrogen Roadmap 2019 [1], it is of tantamount importance to ensure a coherent EU strategy.

As we have seen, both Spain and Norway offer considerable incentives for hydrogen fuel cell cars. Regulators should overcome the chicken-or-the-egg dilemma by developing policies for zero-emission mobility with funding and guarantee mechanisms to unlock investment in refuelling infrastructure [44]. Spain has a more specific target for HRS rollout than Norway, while Norway will take a special responsibility when it comes to bunkering facilities.

The targets for reduction of GHG emissions from the maritime sector are important drivers, considering the limitations of battery-electric solutions and availability of biofuels. Maritime transport is an important focus area and associated with a wide range of support instruments in Norway. The application of green public procurement has been important to facilitate implementation of zero-emission solutions, including hydrogen ships, which are associated with increasing potential towards 2030 and 2050.

Hydrogen for decarbonisation of industry is faced with lock-ins into fossil fuel processes, high capital investments and considerable financial risk, which both Norwegian and Spanish policymakers are working to address. In addition, the industry needs establish horizontal as well as vertical alliances to overcome barriers [1]. Regulators and industry should jointly set out clear, long-term, realistic, and holistic decarbonisation pathways for all sectors and segments.

Last but not least, the assessed policy and regulatory frameworks suggest the need to support research and innovation in energy storage technologies. This should include business models to remove obstacles encountered by investors [10], and measures to ensure that both central production of hydrogen from electrolysis and decentralised solutions providing stability to the grid are adequately incentivised [1].

5 Haeolus Experimental Results on the European Network

In this chapter the simulations performed using the EMPIRE model are presented and discussed. Firstly, input data and general assumptions are specified. Then, the scenarios analysed are described based on the existence of hydrogen demand (either as obligatory or free to satisfy), different nodes producing hydrogen and various demand estimations. Finally, the results are presented and discussed.

5.1 Data

The data used for this set of experiments come from several sources, both in and out of the Haeolus project. They are presented below.

5.1.1 Sources

For the Parameters already in the EMPIRE dataset, the different parameter sources are described in Table 2. Due to the large size of the dataset, numeric values are not presented but can be provided upon request by the authors.

Table 2: Parameters in the EMPIRE model and their sources

Parameters used in EMPIRE model		
Input	**Pyomo parameter**	**Source**
Annual demand	sloadAdjustment	EC reference scenario [46]
Hourly demand	sloadRaw	ENTSO-E [47]
Renewable hourly availability	genCapAvailStochRaw	SUSPLAN [48]
Fuel prices	genMargCost (in spreadsheet)	EC reference scenario [46]
CO_2 prices	genMargCost (in spreadsheet)	EC reference scenario [46]
Hydro annual production	maxHydroNode	[49]
Initial capacity, transmission	transmissionInitCap	SUSPLAN [48]
Max installed transmission	transmissionMaxInstalledCap	ENTSO-E
Max installed generation	genMaxInstalledCapRaw	NREAP [50] (2020 number + 20 %) ZEP TWG ME II for the report 'CCS - Recommendations for transitional measures to drive deployment in Europe' Eurelectric Power statistics (2014). Installed capacity + N × max build bound ENTSO-E Vision 1&2 2030 [51] ReMiX capacities - H.C. Gils et al. (2017) [52] Gianfranco & Erica (5 % of each country's agricultural land area coverage, 7 MW per km^2. Assume 50 % of total area agricultural land). Tradewind's high wind scenario 2030 [53]

Value of lost load	nodeLostLoadCost	London School of Economics report 'The Value of Lost Load (VoLL) for Electricity in Great Britain' [54] on 22 022 €/MWh[12]
Initial capacity, generator	genInitCap	Eurelectric ISO ENTSO-E ZEP [55]
Initial capacity, storage	storPWInitCap/storENInitCap	Same as above
Generator type country availability	GeneratorsOfNode	ENTSO-E
Investment cost, storage	storPWInvCost/storENInvCost	Battery cost median (Cole et al 2016 [56]) 2 014 $/kWh
Investment cost, generation	genInvCost	JCR 2009 (retirement) IEA [57] NEA [58]
Investment cost, transmission	transmissionInvCost	HVAC overhead lines: Average line length: 80 km Investment cost (CAPEX): 50 k€/MW cables: 220 k€/MW converters: 140 k€/MW Compensation costs: 15 % CAPEX yearly O&M costs: 5 % CAPEX yearly Annualised cost: 7 322 €/MW HVDC cables Average line length: 130 km Investment cost (CAPEX): 50 k€/MW cables: 220 k€/MW converters: 140 k€/MW Compensation costs: 15 % CAPEX O&M costs: 5 % CAPEX yearly Annualised cost: 48 190 €/MW

Costs for the fuel cell were chosen in the lower end of the costs. For all cases, it is assumed the costs after 2030 experiment little to no development: electrolyser's costs are assumed to descend from 500 to 450 €/kW from 2035 and stay constant until 2050. In the case of the fuel cell the same happens but from 1 200 to 1 000 €/kW from 2035). The hydrogen parameters are described in Table 3.

[12] 16 940 £/MWh (converted to €/MWh with an assumed exchange rate of 1.3)

Table 3: Hydrogen cost assumptions used in EMPIRE, from [59]. The costs of the hydrogen storage are assumed to be for stationary hydrogen tanks

Large scale PEM Fuel Cell, Electrolyser and storage costs				
Electrolyser	**2017 (SoA)**	**2020 (FCH 2 JU)**	**2024 (FCH 2 JU)**	**2030 (FCH 2 JU)**
CAPEX electrolyser (€/kW)	1 200	900	700	500
OPEX electrolyser (€/kW/a)	24	18	14	11
Electricity consumption at nominal capacity (kWh/kg)	58	55	52	50
Electrical efficiency (% LHV)	57	60	64	67
Fuel cell (0.4-30MW)	**2017 (SoA)**	**2020 (FCH 2 JU)**	**2024 (FCH 2 JU)**	**2030 (FCH 2 JU)**
CAPEX fuel cell (€/kW)	3 000-3 500	2 000-3 000	1 500-2 500	1 200-1 750
OPEX fuel cell (€ ct/kWh)	2.8-5	3	3	2
Electrical efficiency (% LHV)	45	45	45	50
Hydrogen storage	**2017 (SoA)**	**2020 (FCH 2 JU)**	**2024 (FCH 2 JU)**	**2030 (FCH 2 JU)**
Capital costs (€/kg)	400	350	350	350

The original set of the EMPIRE model consists on the following nodes, based on European countries and, in the case of Norway, the different electricity trading regions NO1 to NO-5:

1. Austria
2. Belgium
3. Bosnia and Herzegovina
4. Bulgaria
5. Croatia
6. Czechia
7. Denmark
8. Estonia
9. Finland
10. France
11. Great Britain
12. Greece
13. Germany
14. Hungary
15. Ireland
16. Italy
17. Latvia
18. Lithuania
19. Luxemburg
20. Macedonia
21. Netherlands
22. NO1
23. NO2
24. NO3
25. NO4
26. NO5
27. Poland
28. Portugal
29. Romania
30. Serbia
31. Slovenia
32. Slovakia
33. Spain
34. Sweden
35. Switzerland

The aggregated set, once countries have been aggregated as 'Europe' (misnomer used for simplicity, as it doesn’t include the entirety of the continent) consists of:

1. Belgium
2. Denmark
3. **Europe**
4. Finland
5. France
6. Germany
7. Great Britain
8. Netherlands
9. NO1
10. NO2
11. NO3
12. NO4
13. NO5
14. Spain
15. Sweden

The analysed cases were decided based on different settings ranging from demand satisfaction, the geographical application of this demand and finally demand estimations based on distinct scenarios based on those presented in [1]. Thus, a number of scenarios combining the following settings when relevant have been run:

- Type of hydrogen Demand Satisfaction:
  - No hydrogen in the system: NONE.
  - Hydrogen Demand as a maximum limit in the model: MAX.
  - Hydrogen Demand as a minimum required in the system: MIN.
- Set of Countries for which the Satisfaction applies:
  - Germany, Spain, and four of the Norwegian Nodes (NO2 through NO5) are required to satisfy the demand: SELECTED
  - All countries (including the aggregated 'Europe' node): ALL
- Demand Estimation, from:
  - European demand for hydrogen in 2050 is 2 251 TWh: AMBITIOUS
  - European demand for hydrogen in 2050 is 1 546 TWh: MODERATE
  - European demand for hydrogen in 2050 is 750 TWh: LOW

For each of the three demand estimation cases, the total European demand is distributed to each node according to their GDP as of 2018. Countries with larger economies will receive a larger expected demand. Since only estimated demands for 2015, 2030 and 2050 are available, the rest of the years were linearly estimated between them. Both the LOW and the AMBITIOUS cases were taken from the Hydrogen Roadmap Europe as presented in February 2019 by the FCH JU [1]. The case MODERATE is a middle demand scenario which might be more realistic when it comes to the amount of energy which hydrogen satisfies and which does already come from power generation (as the AMBITOUS scenario might overestimate the latter.)

As it turned out, with the costs (Electrolyser, Storage, and Fuel Cell) as specified, the MAX demand satisfaction is essentially the same as NONE, as no hydrogen is produced 'willingly' without price incentives. We are then left with 7 'actual' cases, which are specified in Table 4.

Table 4 Scenario description analysed with EMPIRE

Scenarios analysed with EMPIRE				
Scenario Name	**Demand Type**	**Demand Estimation**	**Hydrogen Countries**	**Comments**
None	None	NA	NA	Same as the MAX cases since the prices are not enough to justify hydrogen as of now
MinUsualSel	MIN	LOW	SELECTED	
MinUsualAll	MIN	LOW	ALL	
MinModSel	MIN	MODERATE	SELECTED	
MinModAll	MIN	MODERATE	ALL	
MinAmbSel	MIN	AMBITIOUS	SELECTED	
MinAmbAll	MIN	AMBITIOUS	ALL	
MinModAll Reduced Solar	MIN	MODERATE	ALL	Solar max capacity limited to 110 % that of NONE

5.2 Results Summary

For each case, EMPIRE was run to completion, collecting results on storage costs, generation costs, transmission costs, and total cost to the electrical energy system per country included, and aggregated to the European level. Hydrogen price was set to 0, as EMPIRE by itself does not calculate incomes of any type, but rather costs to produce enough power to satisfy a demand.

Some important notes regarding the introduction of hydrogen into the EMPIRE model are considered below:

- Because of the special case of hydrogen being both a part of the system (as storage) and as a potential revenue source, the analysis cannot be said to be completed without adding a way to measure the trade-off between producing hydrogen for storage, and for sale. EMPIRE is an electric network model, and thus adding elements *not* related to electricity production, while possible, might have unintended consequences as market considerations are not included.
- Due to a technical issue, the investment in hydrogen storage is not differentiated between the fuel cell and the electrolyser. This is, a fuel cell is installed wherever an electrolyser is, with the same nominal capacity. This is reasonable only when the majority of the hydrogen produced is used exclusively as storage, and no amount is sold, which is not the case in HAELOUS.
- The model underestimates the necessity of increased transmission *inside the* Europe node. However, as seen from the results later, this is a minor concern as the transmission changes required, while not negligible, are not large or radical enough to warrant concern.

5.2.1 Storage

While the model only requires hydrogen demand to be satisfied in the MIN scenarios, once the investment has been forced, hydrogen is indeed used widely as storage. In the MinAmbAll scenario, the most optimistic of all, installed energy capacity is increased in about 40 % from the no-hydrogen NONE case, while installed power almost quadruplicates. In both cases, it is mostly hydrogen which makes the largest difference, as batteries see increases of less than 50 % and pumped hydropower grows little to nothing compared to the NONE scenario (Figure 2 and Figure 3).

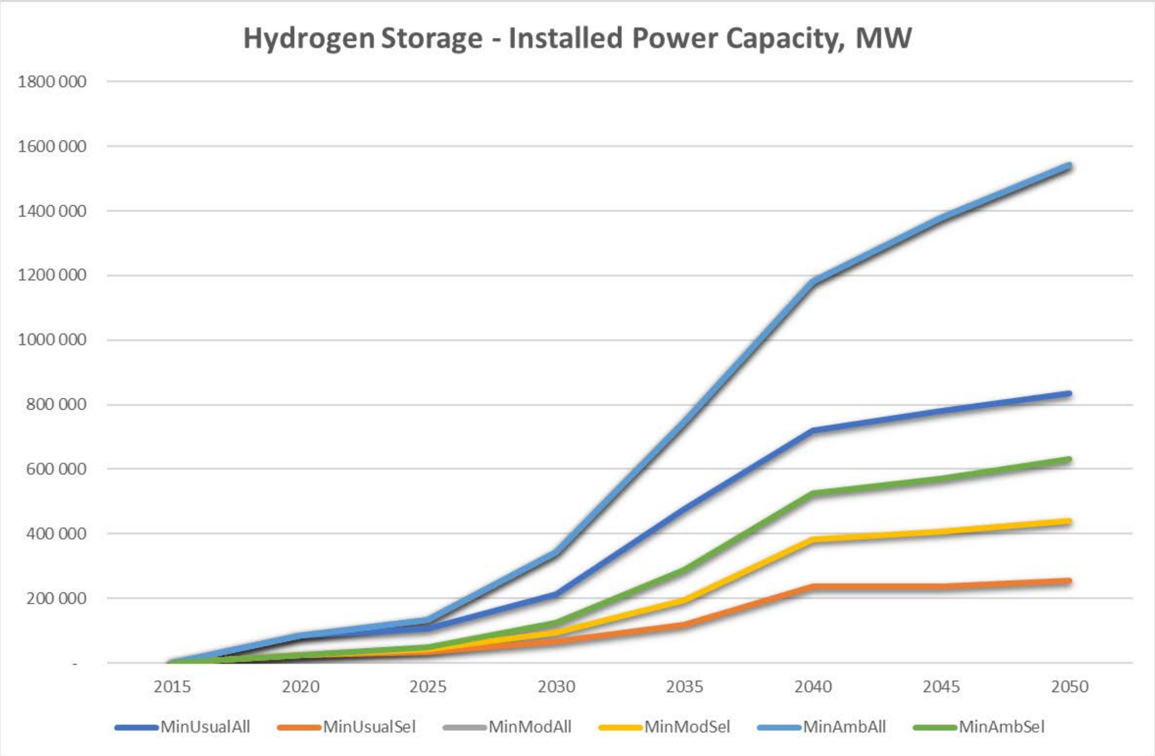

Figure 2: Hydrogen Storage: Investment in power capacity progresses across scenarios as expected

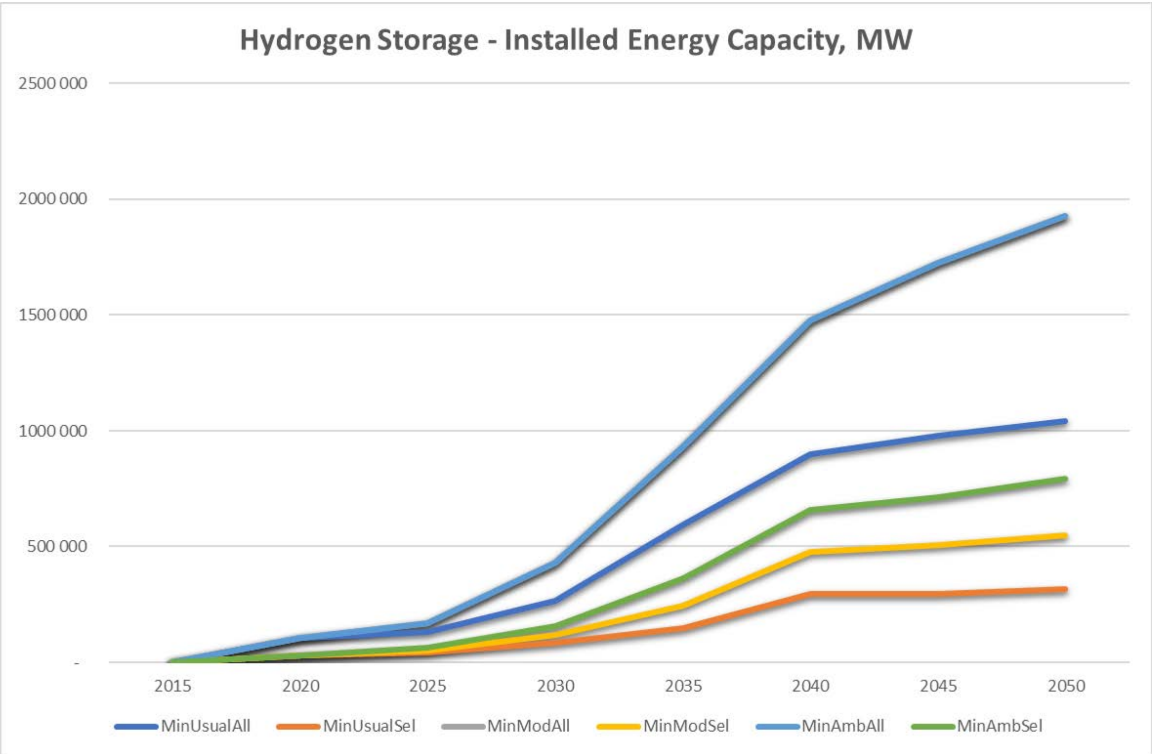

Figure 3: Hydrogen Storage: Investment in energy capacity parallels that of power capacity

As Table 5 and Table 6 show, storage by hydrogen only comes into play once investment has been forced, and not naturally, mainly due to the assumptions of the model. It must be noted, though, that this happens as it is required to install large fuel cells, almost assuredly larger than required by the system needs. This contributes to inflate the price of having hydrogen in the system, and to make the storage more expensive, yet at the same time more relevant, since the capacity is there and, when needed, it is used. Another aspect not included in the model but very relevant is the fact that PEM electrolysers and fuel cells can play an important role to contribute to balancing and frequency regulation in the grid. The ability to change electricity production/consumption makes this system a very relevant component of an energy system with large variable renewable energy generation.

Table 5: Installed Energy Capacity: Scenario Comparison, None v MinUsualAll, all figures in MW

Storage installed energy capacity for none and MinUsualAll scenarios								
	None				**MinUsualAll**			
	Pumped Hydro	**Li-Ion**	**Hydrogen**	**Total**	**Pumped Hydro**	**Li-Ion**	**Hydrogen**	**Total**
2015	2 598 311	5 489	-	2 603 800	2 598 311	5 489	0	2 603 800
2020	2 598 311	5 489	-	2 603 800	2 598 311	5 489	105 161	2 708 961
2025	2 598 311	7 871	-	2 606 182	2 598 311	5 489	131 225	2 735 025
2030	2 598 311	66 090	-	2 664 401	2 598 311	25 800	264 497	2 888 609
2035	2 598 311	78 400	-	2 676 711	2 598 311	113 537	595 654	3 307 501
2040	2 602 795	110 892	-	2 713 687	2 598 932	357 855	900 215	3 857 002
2045	2 602 950	374 581	-	2 977 531	2 602 950	725 086	977 573	4 305 608
2050	2 605 738	533 897	-	3 139 636	2 602 950	763 574	1 042 590	4 409 113

Table 6: Installed Power Capacity: Scenario Comparison, None v MinUsualAll, all figures in MW

Storage installed power capacity for none and MinUsualAll scenarios								
	None				**MinUsualAll**			
	Pumped Hydro	**Li-Ion**	**Hydrogen**	**Total**	**Pumped Hydro**	**Li-Ion**	**Hydrogen**	**Total**
2015	2 598 311	5 489	-	2 603 800	2 598 311	5 489	0	2 603 800
2020	2 598 311	5 489	-	2 603 800	2 598 311	5 489	105 161	2 708 961
2025	2 598 311	7 871	-	2 606 182	2 598 311	5 489	131 225	2 735 025
2030	2 598 311	66 090	-	2 664 401	2 598 311	25 800	264 497	2 888 609
2035	2 598 311	78 400	-	2 676 711	2 598 311	113 537	595 654	3 307 501
2040	2 602 795	110 892	-	2 713 687	2 598 932	357 855	900 215	3 857 002
2045	2 602 950	374 581	-	2 977 531	2 602 950	725 086	977 573	4 305 608
2050	2 605 738	533 897	-	3 139 636	2 602 950	763 574	1 042 590	4 409 113

Discharge of the hydrogen storage, i.e. its relevance to the system as storage medium, is rather significant across demand expectations after 2040. In the cases in which hydrogen is required for all countries, discharge of hydrogen storage remains relatively the same up to 2040, then grows significantly, specially so when moderate or ambitious demand is expected.

5.2.2 Generation

The assumption of increased hydrogen demand is made considering that *whole new sectors* substitute their former energy carriers with hydrogen. This hydrogen has to be produced by renewable electricity in the Haeolus concept. For EMPIRE, large amounts of electricity need to be produced which were not produced before, which is turned into hydrogen. Some of this is sold to new customers, and some is used as storage, chiefly for non-baseload renewable technologies.

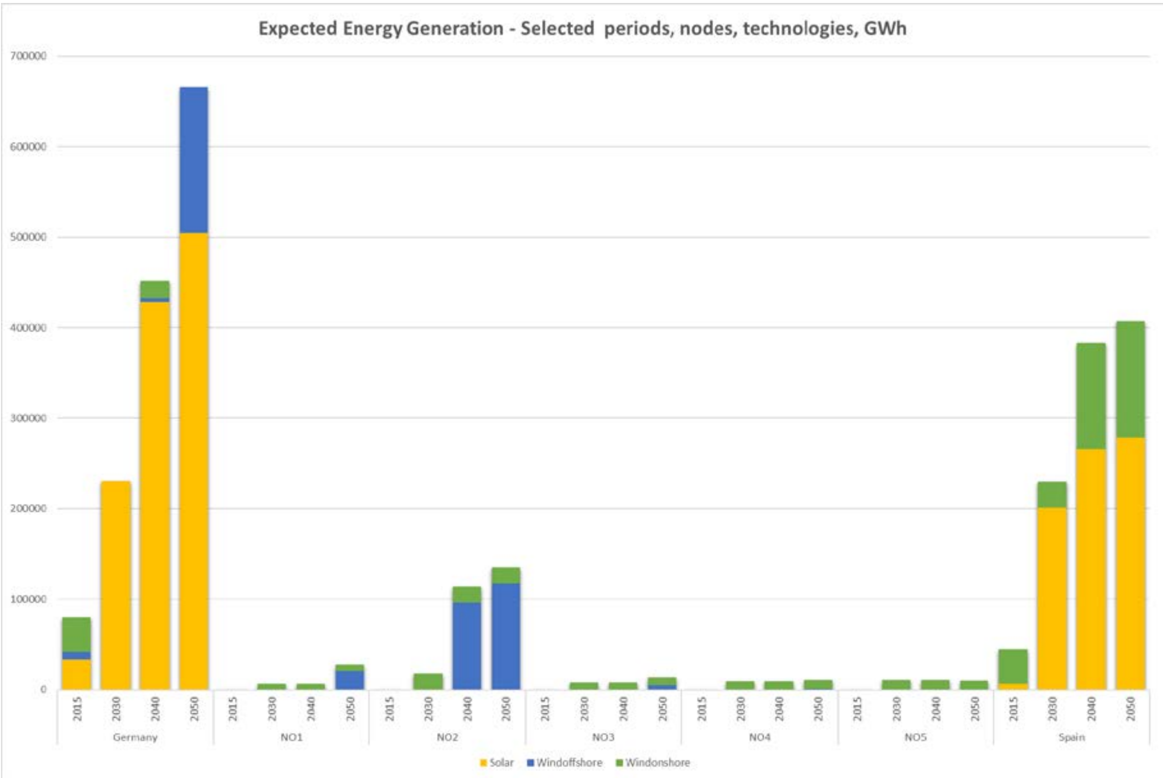

Figure 4 Energy generation by renewable sources, selected figures

As expected, generation in the model increases in all cases compared to the case in which no hydrogen is produced and sold, i.e. the NONE case. As the estimated demand for hydrogen increases, so does too the resulting generation, to a maximum value of 4 767 TWh extra in 2050 in the MinAmbAll case. In the more 'modest' of the MIN cases, MinUsualSel, the production increase is around 613 TWh. The bulk of this generation, both in installed capacity, costs, and production levels, come from countries where hydrogen is being produced. In the case MinAmbSel, where Germany, Norway and Spain are forced to meet an ambitious hydrogen demand (but no other country is), their expected generation by solar power considerably increases, but wind technologies see more modest gains, with Germany almost managing to duplicate its expected generation by 2050, and more than duplicating its installed capacity. Norway sees a small increase in wind production, but overall sees little change, as evidenced in Figure 4.

It is important noting that EMPIRE has rather high upper limit for its generation capacity. It is important to add to the discussion exactly how feasible is it to achieve the production levels required by the model. Generally speaking, though, wind technologies would need to become more competitive compared to solar to make hydrogen-from-wind a solid reality.

While this increase seems daunting, it is good to see that, thanks to the moderate CO_2 prices introduced, the bulk of this comes from renewable sources (Wind and PV solar), fossil fuel consumption falls in comparison to a non-H_2 scenario, and the rest is covered by Nuclear, Hydroelectric and Biofuel. The different aggregated productions for various scenarios are shown in Figure 5.

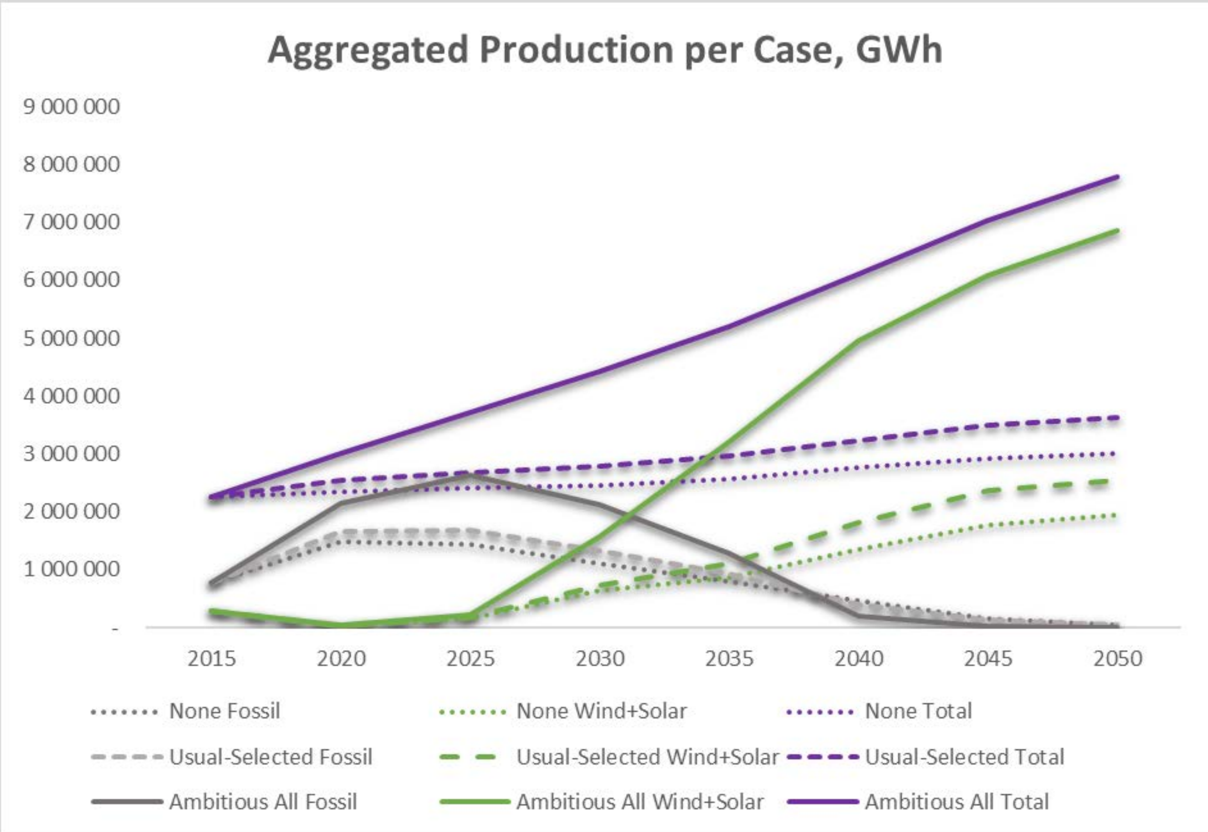

Figure 5: Aggregated production from fossil fuel, PV + Wind and total for the case with no hydrogen 'None', usual hydrogen in 2050 and only certain countries generating and selling it 'MinUsualSel', and the most ambitious case with all countries generating and selling hydrogen 'MinAmbAll'

5.2.3 Transmission

Given the large investment in wind and solar capacity, it was reasonable to expect that transmission would be also increased, given the need to compensate for periods in one node where no generation occurs. While investments in some of the larger connections (France-Europe, Germany-Europe) do see an increase in both capacity and transmission, neither is so extreme as the capacity investment in generation. Hydrogen storage then manages to effectively cover for non-production hours, contributing the system stability.

In most cases, the energy amount transmitted between nodes in the periods 2030-2040 remain comparable equal to the volumes traded in the NONE scenario. This is also true for the total transmitted volumes when hydrogen is produced only in the selected countries, as seen in Figure 6 for all transmission lines of EMPIRE (where the maximum deviation from the NONE scenario is below 12 % for those three scenarios). However, when hydrogen is produced in all countries there is more variation in the scenarios compared to the NONE case during the simulation years, whereas in 2050 the transmitted volume is only 11.85 % larger in the most ambitious scenario (MinAmbitiousAll) compared to the NONE case. Regarding installed transmission capacity, in Figure 7 the total newly installed capacity in the simulation horizon is shown. Apart from the timing where the investment is made, the total transmission capacity is very similar in 2050 (with a maximum deviation of –1.89 % for the MinAmbitiousSelected scenario compared to the NONE case). Some exceptions exist where links in the countries close to the Northern sea are built earlier than in NONE, as it is the case for the connections France-Germany and Germany-Belgium. However, in the cases where all countries produce hydrogen all the new transmission capacity in the connection Europe-Germany is installed later in 2030 whereas in the other scenarios (including NONE) it is divided between 2020 and 2030. Nevertheless, in most cases both the capacity installed, and the volumes transmitted are similar than in a non-hydrogen world.

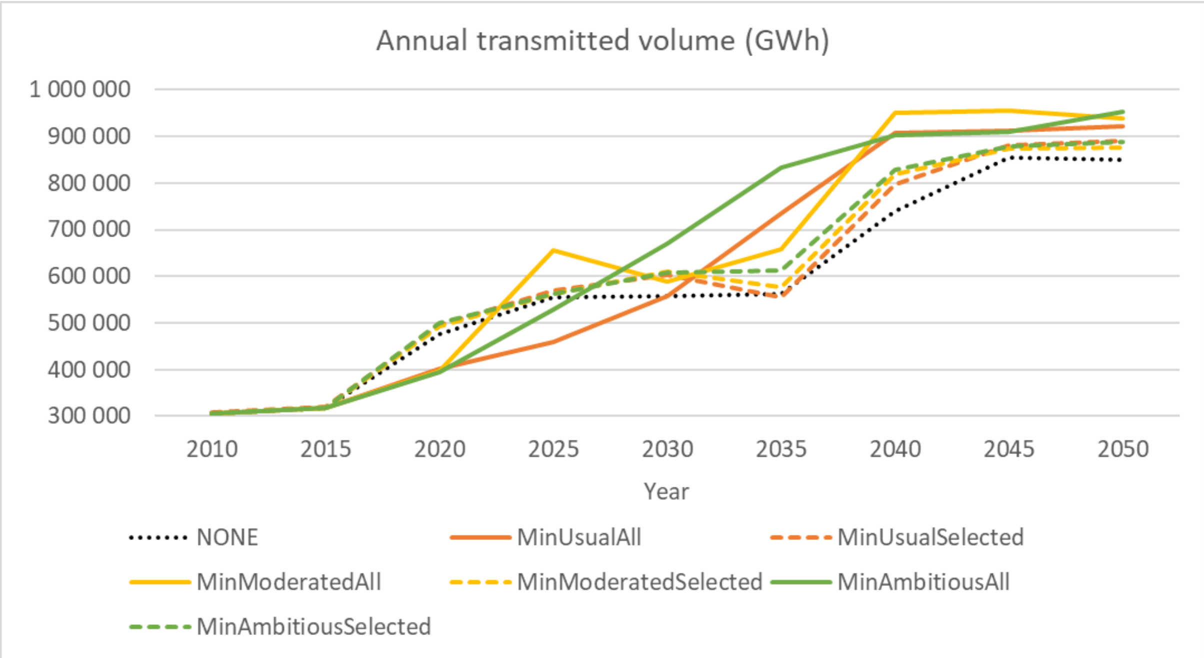

Figure 6: Annual transmitted volume (in GWh) per year and for all relevant scenarios

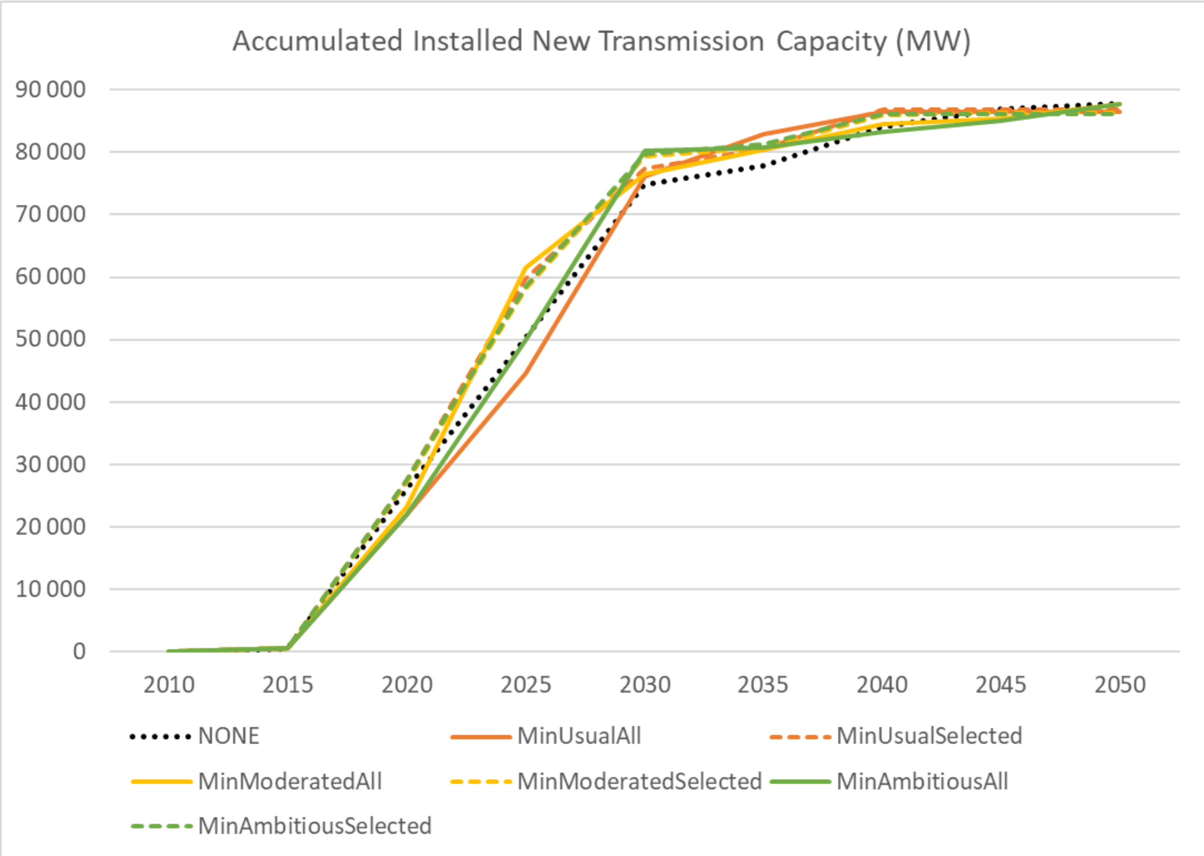

Figure 7: Accumulated Installed New Transmission Capacity (in MW) for the whole European energy system per year and for all relevant scenarios

Because of the small levels in the increases in transmission volumes and capacity, it is difficult to draw conclusions about which scenario between the different possibilities of expected demand and set of countries (the selected or the complete set) is better in terms of reducing changes to the network. This is satisfactory as it indicates that at least this element of the European network would not see a strong impact from a demand of large hydrogen quantities in Europe.

5.2.4 Cost of the Electricity System

The objective of EMPIRE is to minimise the overall cost, for all actors, of generating and transmitting power across the grid. Because hydrogen leaves the system, its production entails a cost EMPIRE cannot capture in its entirety. Sale values are not enough to compensate for the large investments needed to produce the hydrogen, but this does not necessarily mean hydrogen is a net looser in the system. If market values of electricity and hydrogen are considered, then it can be observed that even conservative sale price estimates for hydrogen are mostly enough to compensate for the added cost of generation (and to a lesser degree transmission) in the system, as displayed in Figure 8. The blue area represents the total added system costs whereas the grey area represents the expected income assuming a hydrogen selling price of 2.5 €/kg. This is, unfortunately, besides any infrastructural costs on hydrogen utilisation. It cannot, therefore, be said that hydrogen can be added to the wider energy system at little to no costs to society.

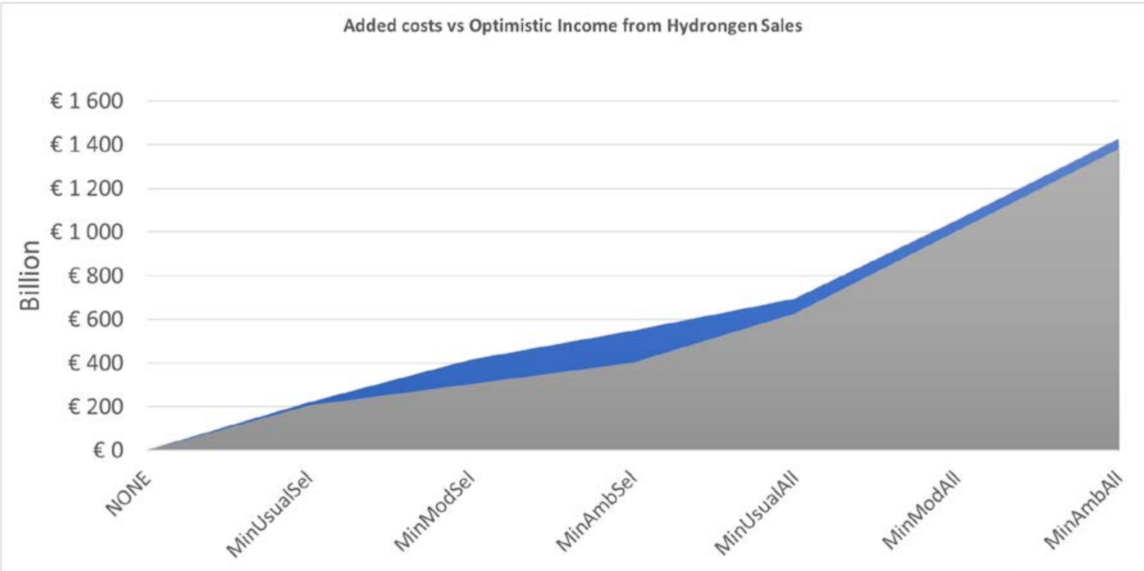

Figure 8: Added costs in the energy system when hydrogen load is added, together with expected income from selling hydrogen, per scenario, assuming a constant cost of 2.5 €/kg.

5.2.4.1 The Haeolus System

However, the results from Figure 8 is only feasible when large amounts of solar power are available to be deployed along with windmills. Solar indeed becomes the largest contributor to the European electricity system when hydrogen is used to power additional demand for energy. Therefore, an additional MinModAll scenario has been run, where the maximum installed capacity of solar energy for each country in the model is limited to a 110 % that of the NONE scenario. This means, after the introduction of hydrogen with a required moderate demand, we permit only a 10 % increase in solar power installed capacity, leaving all other energy sources free to install as much or as little as required.

The model shows this is not terribly economically sensible, as there is an increase of about 9 % of the costs to satisfy the electricity demand, hydrogen production included. The capacity of Combined Cycle natural gas increases, in spite of the CO_2 prices, but it is the only fossil fuel source which grows, compared to the MinModAll scenario without solar restrictions, and this in a minor way in absolute terms. Wind, both onshore and offshore, take up the slack from solar, as desired, and increase their installed capacity by 2050 by six (in the case of offshore) and three (onshore) compared to the free-solar growth scenario.

There is relatively no change in the hydrogen sold, as explained above, so while the grey area of income for this case remains the same, the blue area grows, signifying a loss of profitability in the system when only electricity production/transmission costs are considered, as it can be seen in Figure 9, with the blue area representing again the total system added costs and in grey the expected income (hydrogen price is assumed as 2.5 €/kg).

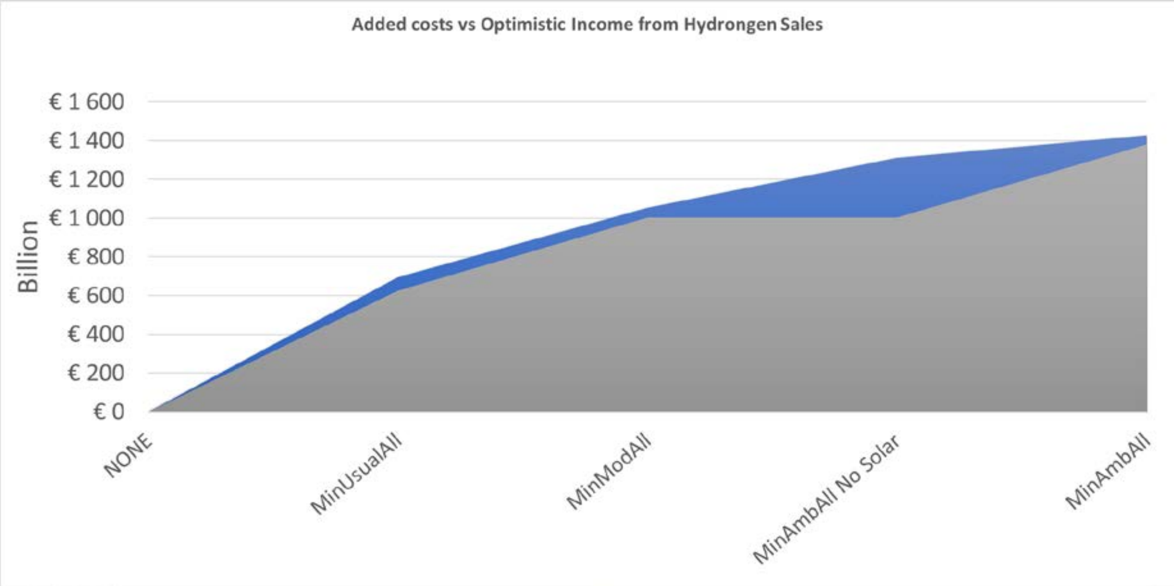

Figure 9: Added costs in the energy system when hydrogen load is added, together with expected income from selling hydrogen, per scenario, adding a case with restricted PV (MinAmbAll No Solar), to promote the Haeolus system wind + hydrogen.

5.3 Beyond Europe: International Perspective

The EMPIRE model does not model the power networks outside of the European continent. This is both due to technical difficulties (the model becomes too complex), and the impossibility to guarantee the quality and stability of the data used to model transmission, generation technologies, time series, and so on. Therefore, there is little that can be said on the international (that is, non-European) context without some additional, *a posteriori* interpretation of EMPIRE results.

First, it is reasonable to assume transmission outside of Europe remains as stable as it does inside of the continent. The amount of energy crossing into or out of Europe increases rather equally in all cases, and so hydrogen from wind in the system seems to have little impact in the transmission.

As shown above, the introduction of hydrogen as storage considerably increases the share of renewable electricity in the system; this is considered to greatly increase Europe energy independence, as both a) the current energy mix depends less on fossil fuels from outside the continent, and b) sold hydrogen, or at least a non-insignificant part of it, goes on to cover energy consumption previously not related to electricity (e.g. as fuel for vehicles, watercraft). These developments can, hypothetically, have impacts beyond Europe as it strengthens its position when negotiating energy policy with foreign actors.

As described in section 4, adoption of hydrogen is a massive undertaking when it comes to policy design, marketing, regulations, public acceptance, and other social aspects. While some regions, such as China or the United States could likely develop both the technology and the policy instruments to achieve a functional hydrogen market, we suggest hydrogen sales could remain in Europe for the time being. If this is true, then hydrogen sales would remain as the experiments above describe, and little international effect would be seen from a wide implementation of Haeolus in Europe in this respect.

6 Concluding Remarks

This section presents this report's main conclusions, as well as final notes, outlook and future work.

The assessment of relevant policies and regulations suggests that there will be a growing demand for hydrogen to decarbonise sectors that otherwise are difficult to decarbonise, i.e. transport, heating and industry. Both Norway and Spain have specific strategies and measures put in place for the transport sector that may drive the development of a market for hydrogen as alternative fuel.

While building heating in Norway for a large part is renewable, Spain has an extensive gas grid and huge potential for emission reductions in this area. Largescale injection of hydrogen into European gas grids will however require harmonisation and revision of the overriding EU regulations.

Hydrogen is regulated as an industrial chemical, but there is the need for more specific guidelines and standards for hydrogen fuel cell solutions also as regards other applications. Green hydrogen for decarbonisation of industry is increasingly in focus, and as it is observed, both Norway and Spain are working to develop further incentives. There is also an increasing focus on sector-coupling and integrated solutions.

After having analysed the scenarios and the results in the previous section, it has been observed that hydrogen storage is not profitable if the only purpose is to storage energy. It does fulfil this role, however, when hydrogen storage (electrolyser, hydrogen tank and fuel cell) needs to be built to fulfil another task (in this analysis to cover hydrogen demand). Then, the hydrogen storage system will be notably used as storage, mainly becoming the main storage technology to cover the fluctuation from extra renewable energy needed to produce the required hydrogen, representing almost 24 % of the storage discharge energy in 2050 when the hydrogen demand begins to be a large part of the total energy demand (cases MinAmbAll and MinModAll, with moderate and ambitious hydrogen demands in all countries). Due to the simplified structure of EMPIRE it is not possible to observe the different roles batteries and hydrogen will have in the future, mainly short-term storage (hours) for the battery and long-term (several days, months) for hydrogen storage, to cover seasonal variations in renewable production. This type of long-term storage is expected to be an important market after 2030 [60], which is also where the importance of hydrogen as a storage increases in the results from EMPIRE, for the aforementioned scenarios with moderate and large hydrogen demand.

The addition of hydrogen demand, which represents an electrification of other sectors (since hydrogen is produced exclusively through electrolysis), makes the total energy demand to increase prominently. This electrification causes the need to consequently increase generation, which is achieved by wind and solar in the performed analyses.

Despite the large increase in generation in all cases, the transmission system is not drastically affected. Only those lines connecting the largest nodes, such as the connections to and from Germany, have a larger net energy flow without a large difference in transmission capacity installed. No big difference is visible in the cases when only the selected countries produce and consume it (Germany, Spain and Norway) and those where all countries produce hydrogen and need to cover the hydrogen demand.

The most ambitious scenario (MinAmbAll), includes a very large increase in energy demand to satisfy the additional hydrogen demand. This causes the energy system's costs to double. Nevertheless, to be able to measure the economic impact, considering a cost of 2.5 € for every kg of hydrogen used to cover the demand, it can be seen that the possible revenues would almost cover the extra costs.

Considering how the costs are linear, the model decides to invest mostly on solar generation, as the costs are lower. However, if the installed capacity for solar energy is restricted (to 110 % of the initial capacity) in the scenario MinAmbAll No Solar, then more wind is installed (resulting in 9 % larger costs), having a larger representation of the Haeolus concept (wind + hydrogen production).

6.1 Final Notes

- The cost ranges of the electrolyser, fuel cell and storage tanks are taken in the lower ranges of those listed. If these are increased, it might be necessary to introduce a higher sale price for the two areas to approach each other.
- Decoupling the size of the investment for the fuel cell from the electrolyser is needed to give a more accurate representation of systems in which hydrogen is not widely used as storage.
- This analysis does not take into account political or physical realities regarding solar panel installation, windmill construction, and so on. These issues should be better addressed in a policy-analysis.
- Equally, the model cannot capture aspects such as market prices, infrastructure needed, or non-cooperation between agents, and thus its solution might be over-optimistic, so it is better treated as a minimum bound to the costs and feasibility.
- Costs in EMPIRE are all linear, so in cases in which a component can either benefit from economies of scale, or the contrary, are not considered by design.
- Future prices are always uncertain, and it affects all technologies.

6.2 Outlook and future work

There are some considerations that would be very interesting to consider in future work. Due to the large dimensions of the European energy system and the limitations of model EMPIRE, not all aspects of the Haeolus concept can be analysed in detail in this deliverable. Future work and other relevant topics are summarised below.

- One first improvement would be to consider the possibility to invest flexibly in electrolyser and fuel cell separately. Thus, it would help to see the relevance of the hydrogen system as a storage system and as a hydrogen provider.
- Extra costs and revenues of the hydrogen system can provide a better understanding of its impact on the energy system. That is: needed infrastructure, a hydrogen market or the provision of balancing and frequency regulation services (in this case considering the changes in the near future, for example the common Nordic balancing model.)
- Consider a more detailed renewable installation, in order to estimate the costs of increased wind and solar generation considering the available resources and the real costs of each specific type of installation.
- The EMPIRE model's objective function is to reduce the total costs of the electricity system to cover a given demand. It assumes perfect cooperation between actors and thus, it would be of interest to study a more detailed approach of the electricity and hydrogen market.
- It can be interesting and relevant to see a comparison of the Haeolus concept with other low carbon hydrogen technologies, such as hydrogen from methane with carbon capture and storage and their relative effect on the European energy system.

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Appendix: Cited legal-administrative documents.

References/links to cited legal-administrative documents are provided in the list below, numbered according to the order of mentioning in main text of the report.

Table 7 List of cited legal-administrative documents

Legal-administrative documents mentioned		
No.	**Document**	**Link / reference**
1	A Clean Planet for All (COM (2018) 773) [A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy]	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018DC0773
2	The Clean Energy for all Europeans package	https://op.europa.eu/en/publication-detail/-/publication/b4e46873-7528-11e9-9f05-01aa75ed71a1/language-en?WT.mc_id=Searchresult&WT.ria_c=null&WT.ria_f=3608&WT.ria_ev=search
3	Electricity Directive (Directive (EU) 2019/944, on common rules for the internal market for electricity and amending Directive 2012/27/EU)	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019L0944
4	Electricity Regulation (Regulation (EU) 2019/943)	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0943
5	The Strategic Energy Technology Plan (SET-plan), EU	https://op.europa.eu/en/publication-detail/-/publication/064a025d-0703-11e8-b8f5-01aa75ed71a1
6	Draft Integrated National Plan for Energy and Climate (NECP 2021-2030), Spain	https://ec.europa.eu/energy/sites/ener/files/documents/es_swd_en.pdf
7	Climate Act (LOV-2017-06-16-60), Norway [Lov om klimamål, 2017]	https://lovdata.no/dokument/NL/lov/2017-06-16-60 (Norwegian only)
8	White Paper on Energy (Meld. St. 25 (2015–2016)), Norway [Energimeldingen, 2016]	English summary: https://www.regjeringen.no/en/aktuelt/white-paper-on-norways-energy-policy-power-for-change/id2484248/ Full text, Norwegian: https://www.regjeringen.no/no/dokumenter/meld.-st.-25-20152016/id2482952/
9	SEVESO Directive [Directive 2012/18/EU, on the control of major-accident hazards involving dangerous substances]	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012L0018
10	ATEX Directive [Directive 2014/34/EU, on the harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres]	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0034
11	Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control) (Recast)	https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:334:0017:0119:EN:PDF
12	The Strategic Environmental Assessment (SEA) Directive [Directive 2001/42/EC, on the assessment of the effects of certain plans and programmes on the environment]	https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32001L0042
13	Environmental Impact Assessment (EIA) Directive [Directive 2011/92/EU, on the assessment of the effects of certain public and private projects on the environment]	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32011L0092
14	Energy Efficiency Directive (Directive 2012/27/EU, on energy efficiency)	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32012L0027
16	Regulation (EU) 2017/2195, establishing a guideline on electricity balancing	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R2195

17	Directive 2008/68/EC, on the inland transport of dangerous goods [RID Directive]	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02008L0068-20190726
18	ADR treaty [European Agreement concerning the International Carriage of Dangerous Goods by Road, 2017]	http://www.unece.org/trans/danger/publi/adr/adr2017/17contentse0.html
19	AND Directive [Directive 2010/40/EU, on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport]	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02010L0040-20180109 Last amended: https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vkj5ppa7vqzk
20	Alternative Fuels Infrastructure Directive (AFID) [Directive 2014/94/EU, on the deployment of alternative fuels infrastructure Text with EEA relevance]	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0094
21	Directive 2009/28/EC, on the promotion of the use of energy from renewable sources	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Aen0009
22	Clean Vehicles Directive [Directive 2009/33/EC, on the promotion of clean and energy-efficient road transport vehicles]	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02009L0033-20190801 Latest amendment: https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vkj5ppa7vqzk
23	The Safety of Life at Sea (SOLAS) Convention [International Convention for the Safety of Life at Sea]	http://www.mar.ist.utl.pt/mventura/Projecto-Navios-I/IMO-Conventions%20(copies)/SOLAS.pdf
24	MARPOL (the International Convention for the Prevention of Pollution from Ships)	http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx
25	Directive 2014/90/EU, on marine equipment	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0090&from=EN
26	Directive 2009/45/EC, on safety rules and standards for passenger ships (recast)	https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:163:0001:0140:EN:PDF
27	Directive 2009/16/EC, on port state control (recast)	https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:131:0057:0100:EN:PDF
28	The Gas Directive [Directive 2009/73/EC, concerning common rules for the internal market in natural gas]	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02009L0073-20190523 Amendment (Directive EU 2019/692): https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0692&from=EN
29	Regulation (EU) 2016/426, on appliances burning gaseous fuels	https://eur-lex.europa.eu/eli/reg/2016/426/oj
30	Regulation on handling of inflammable, reactive and pressurised substances and equipment and facilities used in the handling of such substances [Forskrift om håndtering av brannfarlig, reaksjonsfarlig og trykksatt stoff samt utstyr og anlegg som benyttes ved håndteringen, FOR-2009-06-08-602] Norway	Available in Norwegian only: https://lovdata.no/dokument/SF/forskrift/2009-06-08-602
31	Control of Major Accident Hazards Involving Dangerous Substances Regulation, 2016 [Forskrift om tiltak for å forebygge og begrense konsekvensene av storulykker i virksomheter der farlige kjemikalier forekommer (storulykkeforskriften)] Norway	Available in Norwegian only: https://lovdata.no/dokument/SF/forskrift/2016-06-03-569
32	Royal Decree 656/2017 – Regulation of Storage of Chemical Products and its Complementary Technical Instructions, Spain	Available in Spanish: https://www.boe.es/eli/es/rd/2017/06/23/656

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34	Regulation on electrical low voltage installations [Forskrift om elektriske lavspenningsanlegg] last amended 01.06.2016. Norway	https://lovdata.no/dokument/SF/forskrift/1998-11-06-1060
35	Regulation on preventive security and contingency in energy supply [Forskrift om forebyggende sikkerhet og beredskap i energiforsyningen (Beredskapsforskriften), FOR-2012-12-07-1157] Norway.	https://lovdata.no/dokument/SF/forskrift/2012-12-07-1157#KAPITTEL_1
36	Descriptive guide to the Grid connection procedure, Spain	https://www.hylaw.eu/database/national-legislation/spain/-descriptive-guide-to-the-grid-connection-procedure-
37	Regulation to control pollution [Forurensningsforskriften, FOR-2004-06-01-931] last amended in 2016, Norway	Norwegian full-text: https://lovdata.no/dokument/SF/forskrift/2004-06-01-931?q=forurensningsforskriften
38	Spain, Royal Decree 1955/2000, Regulating the connection and access of electricity to the grid and the transmission and distribution of electricity [Real Decreto 1955/2000, por el que se regulan las actividades de transporte, distribución, comercialización, suministro y procedimientos de autorización de instalaciones de energía eléctrica]	Renewable energy policy database and support – RES-LEGAL EUROPE, National profile: Spain. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2000-24019
39	Electricity Act 24/2013 [Ley 24/2013, de 26 de diciembre, del Sector Eléctrico]	Spanish full-text: https://www.boe.es/buscar/doc.php?id=BOE-A-2013-13645
40	Royal Decree 900/2015 regulation of the supply and generation of electricity for self-consumption. [Real Decreto 900/2015, de 9 de octubre, por el que se regulan las condiciones administrativas, técnicas y económicas de las modalidades de suministro de energía eléctrica con autoconsumo y de producción con autoconsumo]	Spanish full-text: https://www.boe.es/eli/es/rd/2015/10/09/900
41	Royal Decree Law 15/2018, 5 October, of urgent measures for energy transition and the protection of consumers (the “RD-Law”), Spain	https://www.osborneclarke.com/insights/the-main-novelties-of-the-royal-decree-law-152018-5-october-on-urgent-measures-for-the-energy-transition-and-the-protection-of-consumers/
42	Royal Decree-Law 1/2019, of 11 January, of urgent measures to bring the competencies of the Spanish National Markets and Competition Commission ("CNMC") in line with the requirements of EU law in relation to Directives 2009/72/EC and 2009/73/EC, Spain	https://www.lexology.com/library/detail.aspx?g=98ede6fd-1188-412c-9d39-251178729604
43	Directive 2009/72/CE Directive 2009/72/EC, concerning common rules for the internal market in electricity	https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0072
44	Directive 2008/68/EC, on the inland transport of dangerous goods (recast)	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02008L0068-20190726 Latest amendment (Regulation (EU) 2019/1243): https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32019R1243
45	The Transportable Pressure Equipment Directive (TPED) (Directive 2010/35/EU)	https://eur-lex.europa.eu/eli/dir/2010/35/oj
46	International Maritime Dangerous Goods (IMDG) Code, 2006	http://www.imdgsupport.com/free%20imdg%20code%20introduction%2037-14.pdf

		https://law.resource.org/pub/us/cfr/ibr/004/imo.imdg.1.2006.pdf
47	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC) Code (IMO MSC 5(48))	https://www.mardep.gov.hk/en/msnote/pdf/msin1547anx1.pdf
48	Regulation on maritime transport of dangerous goods, Norway [Regulations of 21 May 1987 No. 406 concerning carriage by ship of special or dangerous cargoes in bulk or as packaged goods]	Translated English version, University of Oslo: https://app.uio.no/ub/ujur/oversatte-lover/data/for-19870521-0406-eng.pdf
49	Act 14/2014 of 24 July on Maritime Navigation (the Maritime Navigation Law or MNL), Spain	https://www.mjusticia.gob.es/cs/Satellite/Portal/1292427275074?blobheader=application%2Fpdf&blobheadername1=Content-Disposition&blobheadervalue1=attachment%3B+filename%3DAct_14_2014__dated_24th_july__on_Maritime_Navigation_%28Ley_de_Navegacion_Maritima%29.PDF
50	Norway Guideline on transport and distribution of petroleum in onshore pipelines [Temaveiledning om transport og distribusjon av petroleum i rørledning over land)] Directorate for Civil Protection	Available in Norwegian only: https://www.dsb.no/globalassets/dokumenter/farlige-stoffer-npf/industrisikkerhet/temaveiledning_transport_distribusjon_petroleum_roerledning_over_land.pdf
51	Law 34/1998, on the hydrocarbons sector, Spain	https://www.boe.es/buscar/act.php?id=BOE-A-1998-23284 2015 amendment: https://www.boe.es/boe/dias/2015/05/22/pdfs/BOE-A-2015-5633.pdf
52	Directive 2007/46/EC, establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles (Framework Directive).	https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32007L0046
53	Regulation EC 79/2009, on type-approval of hydrogen-powered motor vehicles	https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:035:0032:0046:en:PDF
54	Public Procurement Act [Lov om offentlige anskaffelser, LOV-1999-07-16-69] in force from 01.01 2017	Available in Norwegian only: https://lovdata.no/dokument/NL/lov/2016-06-17-73?q=anskaffelsesloven
55	Regulation on Public Procurement (Forskrift om offentlige anskaffelser (anskaffelsesforskriften), in force from 01.01.2017, Norway	Norwegian full-text: https://lovdata.no/dokument/SF/forskrift/2016-08-12-974?q=forskrift om offentlige anskaffelser
56	Directive 2014/94/EU, on the deployment of alternative fuels infrastructure [the AFID Directive]	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=EN
57	Regulation of pressure equipment (Forskift om trykkpåkjent utstyr,), of 11th October 2017	Available in Norwegian only: https://lovdata.no/dokument/SF/forskrift/2017-10-10-1631?q=trykkp%C3%A5kjent%20utstyr
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59	Royal Decree 639/2016, Spain, on the alternative fuels infrastructure	https://www.boe.es/diario_boe/txt.php?id=BOE-A-2016-11738
60	Norway Action plan for infrastructure for alternative fuels in transport [Handlingsplan for infrastruktur for alternative drivstoff i transport], 1. July 2019.	Available in Norwegian only: https://www.regjeringen.no/contentassets/67c3cd4b5256447984c17073b3988dc3/handlingsplan-for-infrastruktur-for-alternative-drivstoff.pdf
61	Regulations of 27 December 2016 No. 1883 on ships using fuel with a flashpoint of less than 60°C. Norwegian Maritime Authority	https://www.sdir.no/contentassets/627b963904e54f89994b41c01fe6a410/27-december-2016-no.-1883-ships-

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62	MSC.1/Circ.1455 – guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments.	https://www.mardep.gov.hk/en/msnote/pdf/msin1339anx1.pdf
63	EU Guidelines for System Operations and Energy Balancing [Commission regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing]	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R2195&from=EN
64	Royal Decree 244/2019, of 5 April, Spain regulates the administrative, technical and economic conditions for the self-consumption of electricity	https://ca.practicallaw.thomsonreuters.com/0-521-6274?transitionType=Default&contextData=(sc.Default)
65	Regulation to control pollution, last amended in 2016, [Forskrift om begrensning av forurensning (forurensningsforskriften)], Norway	https://lovdata.no/dokument/SF/forskrift/2004-06-01-931
66	Spain, Ley 16/2013, de 29 de octubre, por la que se establecen determinadas medidas en materia de fiscalidad medioambiental y se adoptan otras medidas tributarias y financieras.	The EU Environmental Implementation Review 2019 Country Report – SPAIN: https://ec.europa.eu/environment/eir/pdf/report_es_en.pdf . Spanish text: https://www.boe.es/boe/dias/2013/10/30/pdfs/BOE-A-2013-11331.pdf
67	The Government's action plan for green shipping, Norway [Handlingsplan for grønn skipsfart], issued 20. June 2019	https://www.regjeringen.no/contentassets/2ccd2f4e14d44bc88c93ac4effe78b2f/the-governments-action-plan-for-green-shipping.pdf