H₂AEOLUS

Techno-economic analysis of wind-hydrogen integration

Maider Santos, Raul Rodriguez and Santiago Garcia (Tecnalia). Sigrid Damman and Ulf Johansen (Sintef)

Quality Assurance: Valerio Mariani (UniSannio)

Project acronym:	HAEOLUS
Project title:	Hydrogen-Aeolic Energy with Optimised eLectrolysers Upstream of Substation
Project number:	779469
Call:	H2020-JTI-FCH-2017-1
Topic:	FCH-02-4-2017
Document date:	May 28, 2020
Due date:	December 31, 2019
Keywords:	Wind farm, electrolyser, hydrogen, LCOH2

Abstract: Tecnalia will evaluate the applicability of the design in other conditions, and will suggest modifications for similar plants in different kinds of wind farms (e.g. offshore, single-turbine, large farms, etc.), considering at least three case studies from actual wind farms. SINTEF will support the task in the socio-economic evaluation of such plants, their profitability and their potential for job creation and effect on local and national economies. SINTEF shall also report on the applicable regulations, codes and standards for such applications for all case studies identified by Tecnalia.

Revision History

Date	Description	Author
2019/Oct/31	First draft	Maider Santos (Tecnalia)
2020/Mar/2	QA	Valerio Mariani (UniSannio)
2020/Mar/9	QA	Sigrid Damman (SINTEF)
2020/Apr/3	QA	Ulf Johansen (SINTEF)
2020/Apr/23	Final version including QA suggestions	Maider Santos (Tecnalia)
2020/May/26	Revised version	Maider Santos (Tecnalia)

Table of Contents

List of Figures

List of Tables

Acronyms and glossary of terms

CAPEX	Capital expenditures
EU	European Union
ELY	Electrolyser
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
H_2	Hydrogen
IP	Investment Payback
LCOE	Levelized cost of Energy
LCOH2	Levelized cost of hydrogen
LCOS	Levelized cost of storage
MAWP	Multi-Annual Work Program
M€	Million (10^6) euros
Nm^3	Normal cubic meter
NPV	Net present value
OPEX	Operational expenditures
PEM	Proton Exchange Membrane
POC	Point of Connection
PV	Present value
RES	Renewable energy system
SNG	Synthetic Natural Gas
SOC	State of Charge

1 Introduction

The present document is a deliverable of the HAEOLUS project, an EU co-funded project that proposes the integration of a new-generation 2.5MW PEM electrolyser in a 45MW wind farm. The project will demonstrate different control strategies to enhance the techno-economic performance of the system.

The project will demonstrate a 2.5MW PEM electrolyser and a 120kW fuel cell, limited to 100kW due to regulatory constraints, for re-electrification, with a target cost for the electrolyser of 3.7M€/(t/d). A 2.5 years demonstration is planned, producing 120 tonnes of hydrogen.

The Wind-H_2 system will be operated in different modes, as per the IEA Task 24 final report [1]. Among these, one provides grid services as power-smoothing (energy-storage use case), one provides the local load demand tracking (mini-grid use case) service and the third provides the hydrogen production (fuel-production use case) service. In all three use cases, the electrolyser will generate H_2 accordingly. However, only when the operations are related to the fuel-production use case, the H_2 will be enabled to be used in other applications out of the fence of the wind farm, as for example powering fishing boats, transportation and/or industrial processes, among others. Since specific demand profiles and reference prices for the H_2 have yet to be defined, the reported studies do not take into account for any income from the sale of the produced H_2.

This deliverable explains in detail the work carried out within the task 5.2 regarding the applicability of the design in different conditions for similar plants in alternative kinds of wind farms considering three locations and their corresponding wind farms, namely Raggovidda, Smøla and Mocayuelo.

The electrolyser performance is studied for the three locations, which are further described in section 4.6. For each location, several scenarios depending on various electrolyser operating strategies and sizes are presented and briefly sketched for clarity as follows:

Optimal H_2 production Operation of the electrolyser based on the spot market energy prices, producing H_2 when the price is below a certain threshold.

Congestions management The electrolyser is used to optimize the economic performance of a wind farm with an installed capacity higher than the connection point export capacity.

Secondary frequency regulation (Spanish ancillary market) Secondary frequency regulation is an optional ancillary service with the purpose of maintaining the generation-demand balance, by correcting deviations with respect to the anticipated power exchange schedule of the 'Spain' Control Block, and the system frequency deviations. Its temporary action horizon ranges from 20 seconds to 15 minutes. This service is remunerated by means of market mechanisms via two concepts: availability (control band) and usage (energy). The electrolyser, together with the wind farm, operates in order to provide this service [2].

Additionally, the socio-economic impact of the Wind-H_2 system has been evaluated, as well as the profitability and their potential for job creation and effect on local and national economies.

1.1 Document content description

This report is organized as follows. In section 2 the Wind-H_2 integrated system is described including main data of the components. Section 3 describes the analysed three wind farms, Raggovidda, Smøla and Moncayuelo. Section 4 details the methodology, main calculations, scenarios and case studies. Section 5 details the socio-economic evaluation methodology, including a qualitative assessment of relevant regulations, codes and standards and of the obtained results. Finally, conclusions and next steps are presented in section 6.

2 Reference Model of the Wind-Hydrogen Integrated System (Wind-H_2)

The integrated Wind-H_2 system consists mainly of five components, as Figure 1 shows, that is the wind farm, the substation, the electrolyser, the storage tank and the fuel cell. Figure 1 also highlights the general architecture of the system. The wind farm includes 15 turbines 3MW each and is described in detail in section 3.1 while section 2.1 reports the reference data of the electrolyser and section 2.2 reports the reference data of the fuel cell and of the storage tank. General financial data are shown in section 2.3 [3].
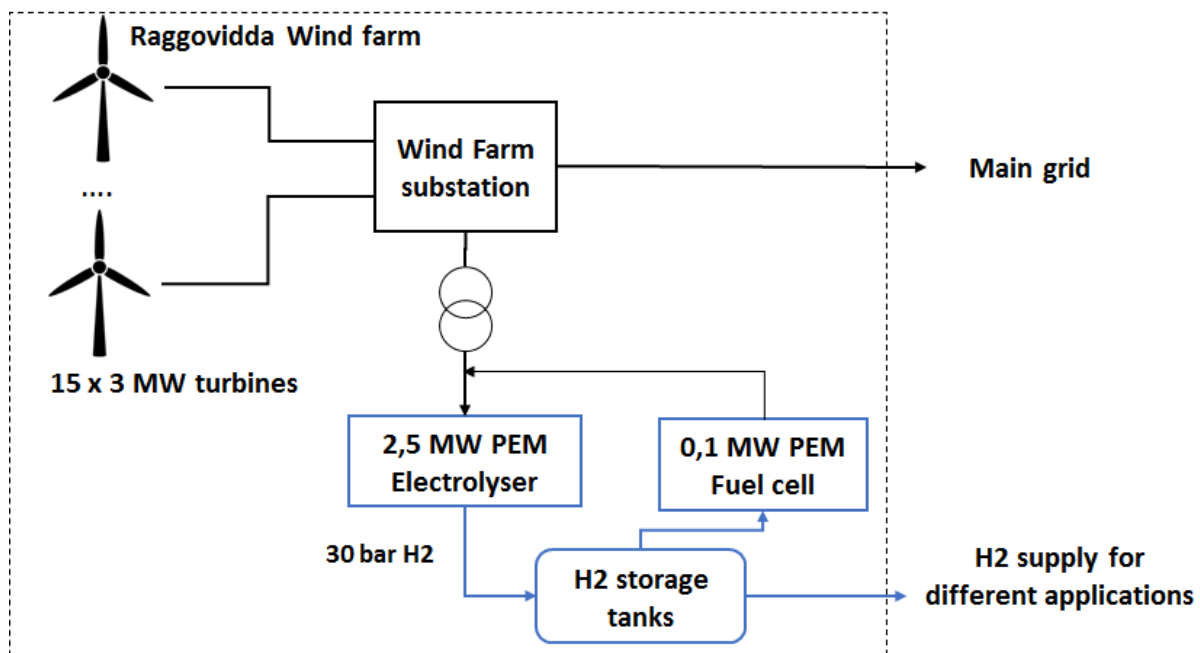
Figure 1. Wind-H_2 system's architecture.

2.1 Electrolyser Data

An electrolyser is an electrochemical device that converts electricity into H_2. Among the several activities that will be carried out as pertaining to the HAEOLUS project, a 2.5MW PEM electrolyser developed by Hydrogenics will be also integrated. Table 1 summarises the main characteristics of the electrolyser that were also used for the techno-economic simulations. The data correspond to the 2017 Multi-Annual Work Program (MAWP) target [4].

Table 1. 2.5MW Hydrogenic electrolyser PEM data.

2.5MW PEM Electrolyser	
Parameter	**Value**
Nominal Power	2.5MW
Minimum Power	0.3MW
Maximum Power	3.25MW
Efficiency	see Figure 2
Efficiency degradation at rated power and considering 8000 h operations / year	2%/year
Hydrogen delivery pressure	30bar
Hydrogen production rate	45kg/hour
Start-up time (cold start)	1,200 seconds
Response time (warm start)	30 seconds
Shut down time (transition to standby)	1 seconds
Switch off time (include depressurization)	2 minutes
Ramp rate up/down	60MW/min
Standby consumption	1kW
Calendar life	20 years
Cycle-life	5,000 on/off cycles
	40,000 operation hours
CAPEX-electrolyser	1,328€/kW
OPEX per installed MW	60€/MW year
Overhaul costs (*)	354€/kW

(*) Overhaul cost are mainly related to the stack replacement.

Regarding the electrolyser efficiency it is important to note that it is not a constant value since it depends on the direct current (Idc) consumption of the stack. As it can be seen from Figure 2, the PEM stack's energy consumption per H_2 unit (Nm^3) increases linearly with the direct current, so that the efficiency slightly worsens with the increase of H_2 production. However, this curve is affected by the auxiliary consumptions and the efficiency curves of the power converters, so that the overall efficiency curve changes and the optimal efficiency is approximately at the 20% of the production rate.
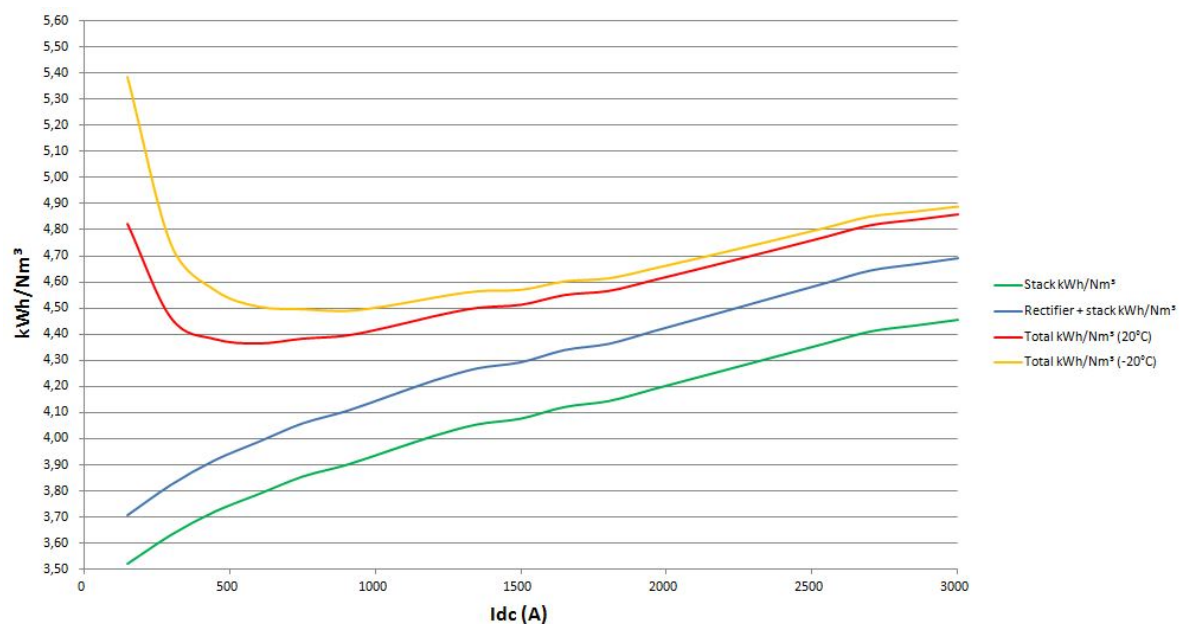
Figure 2. Electrolyser efficiency curve.

The FCH 2 JU Multi-Annual Work Plan (MAWP) for years 2014-2020 set cost and performance targets for electrolysers, in general, that have been considered in the reported studies along with sensitivity analyses that have also been carried out according to the next KPIs.

Table 2. FCHU MAWP 2014-2020 targets for electrolysers [4].

		State-of-the-art	2017	2020	2023
KPI 1	H2 production electrolysis, energy consumption (kWh/kg) @ rated power	57-60 @100kg/d	55 @500kg/d	52 @1000+kg/d	50 @1000+kg/d
KPI 2	H2 production electrolysis, CAPEX @ rated power including ancillary equipements and comissioning	8.0 M€/(t/d)	3,7 M€/(t/d)	2.0 M€/(t/d)	1.5 M€/(t/d)
KPI 3	H2 production electrolysis, efficiency degradation @ rated power and considering 8000 H operations / year	2% - 4% / year	2% / year	1,5% / year	<1% / year
KPI 4	H2 production electrolysis, flexibility with a degradation < 2% year (refer to KPI 3)	5% - 100% of nominal power	5% - 150% of nominal power	0% - 200% of nominal power	0% - 300% of nominal power
KPI 5	H2 production electrolysis, hot start from min to max power (refer to KPI 4)	1 minute	10 sec	2 sec	< 1 sec
	H2 production electrolysis, cold start	5 minutes	2 minutes	30 sec	10 sec

2.1.1 Electrolyser Operation & Degradation

The electrolyser to be installed in Raggovidda has 3 operating modes:

Off The electrolyser is not generating H_2, is depressurized and there is no energy consumption.

Standby The electrolyser is not generating H_2, is pressurized and the energy consumption of 1kW of order of magnitude.

On The electrolyser is generating H_2 and the energy consumption depend on the H_2 generation.

To shift from one operating mode to another the electrolyser takes some time and consumes some energy. Relevant time intervals are:

Start-up time (cold start, 1200 seconds) This is the time to pass from off to full production. During this time the power consumption is limited to approximately 50% of the rated power. Likewise, the production during this time is limited to approximately 50% of the rated capacity.

Response time (warm start, 30 seconds) This is the time to pass from standby (zero H_2 production) to full production. During this time the consumption varies form a few kilo watts (maximum 15kW) the first 15s to 2.5MW (maximum) linearly.

Shut down time (1 second) This is the time to shift from production to standby.

Switch off time (120 seconds) This is the time to shift to off (depressurised).

However, the studies reported in the present document rely on several assumptions based on some facts. Firstly, the electrolyser is never considered to switch off, so that when it is not producing H_2 it is in standby where its consumption is of 1kW of order of magnitude just for keeping the stacks warm. This allows to achieve shorter on/standby (and vice versa) switching times with respect to those implied by on/off commutations and to use less nitrogen for purging. On the other hand, the real time optimal operations strategy will be studied in detail in WP6 – Control [5], [6] and WP8 – Demonstration [7], [8], [9].

Secondly, since the electrolyser efficiency degrades depending on its usage, a relative[1] efficiency decrease of 2% at rated power and per 8,000h of operation has been also considered.

Thirdly, the electrolyser useful life is affected by both calendar- and cycle-life. The electrolyser has an estimated maximum life of 20 years but depending on the usage the lifetime can be shortened. The cycle-life is determined by assuming 40,000 working hours and 5,000 on/off switching cycles. However, taking into consideration the operation strategy that has been applied in these studies, the cycle-life will be only determined by the working hours.

Once the electrolyser overpasses its useful life, the life can be extended by a major overhaul that includes the stack substitution. This overhaul cost is lower than a complete replacement, being estimated in approximately 25% of the initial CAPEX.

---

[1] These efficiency degradation is a relative value, thus, e.g. if the efficiency is 98% the efficiency degradation after 8,000 hours is 1.96%.

2.2   Fuel Cell and Storage Tank

The produced H_2 is stored in a 300 bar tank[2] and then is used by the fuel cell in order to produce electricity. Main characteristics of the storage system are shown in Table 3.

Table 3. H_2 storage system data.

Hydrogen plant data		
Parameter	**Value**	**Unit**
MP H2 tank volume	64	m^3
MP H2 tank pressure	30	Bar
HP Compressor nominal power	200	kW
HP Compressor & other balance of plant elements power consumption average power	80-120	kW
MP & HP Calendar life	20	Years
MP & HP Cycle life (if it makes sense for the compressor)	5,000	Cycles
	40,000	Working hours
HP CAPEX-tank (1.352M€)	830	€/kg
HP CAPEX-compressor	350,000	€
HP Compressor Life	15	Years
OPEX per installed MW (HP compressor)	4	% (CAPEX)

A fuel cell is an electrochemical system that transforms chemical energy of H_2 or other fuel into electricity (direct current). The fuel cell consumes H_2 and O_2 and produces electricity, heat and water.

As part of the HAEOLUS project, a 120kW fuel cell manufactured by Hydrogenics as part of INGRID EU co-founded project [10] and limited to 100kW due to regulatory constraints, will be installed in order to re-electrify the produced H_2 while the related local market is being developed. Table 4 and Figure 3 briefly report the fuel cell data and the efficiency curves from Hydrogenics, respectively.

---

[2] The storage foreseen in the Haeolus project is just 30 bar. However, it is expected that developments beyond the project will require 300 bar tanks.

Table 4. 120kW Hydrogenics fuel cell data.

PEM Fuel Cell		
Parameter	**Value**	**Unit**
Nominal Power	0,12	MW
Minimum Power	0,012	MW
Maximum Power	0,132	MW
Efficiency curve (please describe which elements are included in this figure)	See Figure 3	%
Efficiency derating due to usage or time	-	%/year
Hydrogen consumption rate (theoretically should be possible to obtain this number from power and efficiency)	9	kg/hour
Response time (warm start)	300	Seconds
Shut down time	-	Seconds
Ramp rate up/down	0,024	MW/min
Standby consumption	0,4	kW
Calendar life	10	Years
Cycle-life	5.000	Cycles
	40.000	Working hours
CAPEX-Fuel cell	2.250.000,00	€/MW
OPEX per installed MW	45.000,00	€/MW year
OPEX per produced MWh	-	€/MWh year
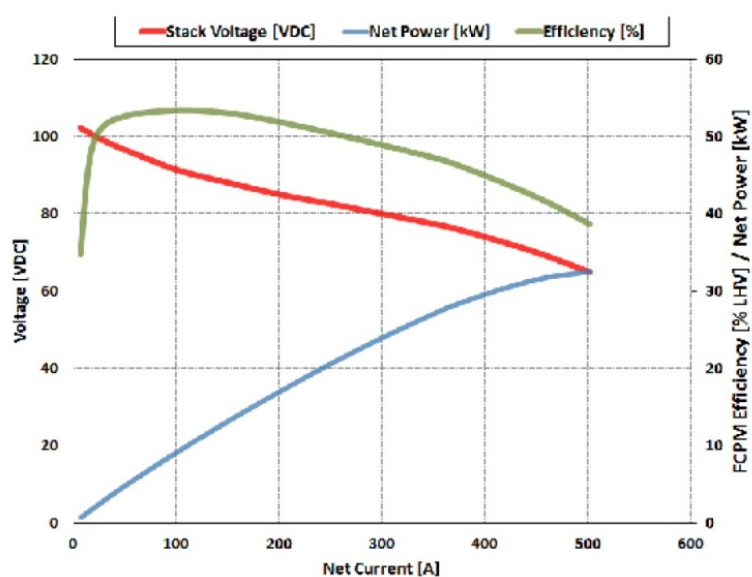
Figure 3. Fuel cell efficiency curve.

2.3 General Financial Data

Table 5 shows the financial data used for the studies.

Table 5. Financial data.

Financial Data	
Parameter	**Value**
Analysis period	20 years
Discount rate (including inflation)	6%
Inflation	2%
Debt per cent (over the investment)	60%
Debt interest rate	3%
Loan term	15 years

3 Identification and Description of Case Studies

The main objective of the present document is to analyse the operation of the integrated system (Wind-H$_2$) and the coordinated operation of all the parts from a techno-economical perspective in order to achieve its optimal sizing . To this aim three different case studies (Raggovidda, Smøla and Moncayuelo) from actual wind farms under different working scenarios are considered.

The studies have been carried out by means of a TECNALIA's proprietary tool for energy storage systems design, that has been adapted with a H$_2$ components library specifically developed within HAEOLUS project. The tool permits to carry out time-based techno-economic simulations of the operation of the electrolyser, the tank and the fuel cell in the three different scenarios. The tool also allows sensitivity analyses with respect to the several parameters that may affect the overall system performance. The results are showed through the graphical user interface reported in Figure 4 and are exported to an excel file.
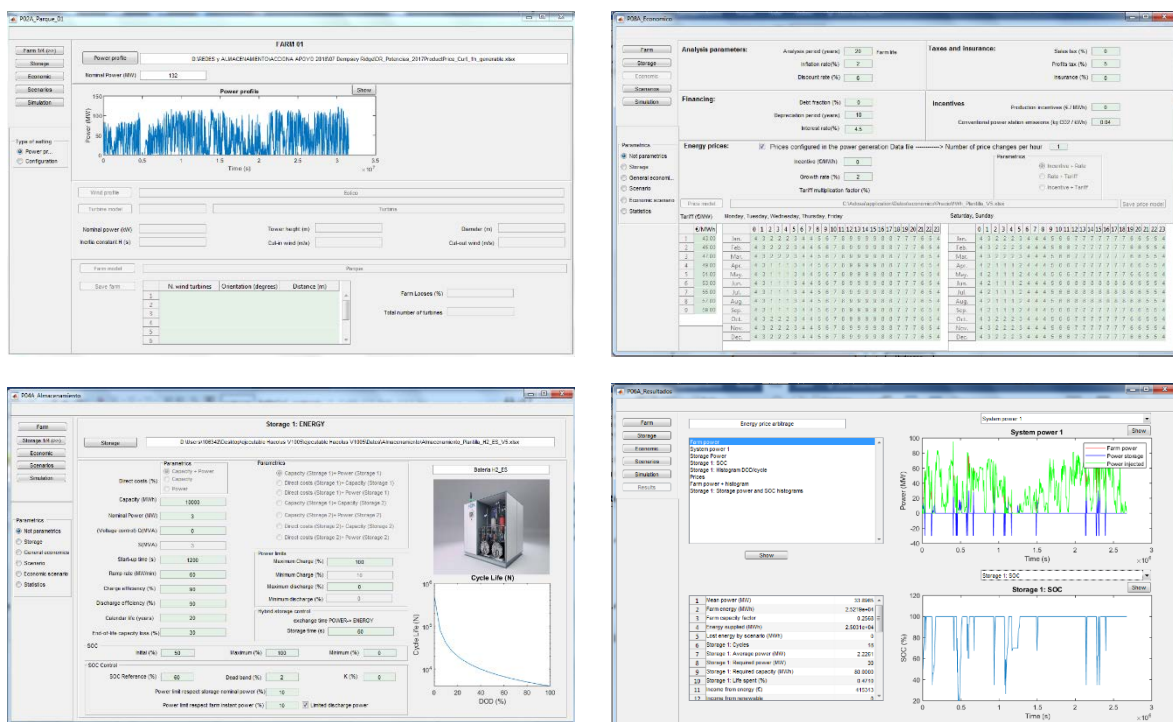
Figure 4. Main configuration and results screen of the Hydrogen and energy storage techno-economic analysis tool.

For each case study (Raggovidda, Smøla and Moncayuelo), several scenarios and use cases are presented, mainly related to various electrolyser operating strategies and sizes. In all of them, the Levelized Cost of Hydrogen (LCOH2), as defined in D5.1 [3], is used to compare the suitability of the solutions. The LCOH2 is the sale price of the produced hydrogen in order to achieve the same Net Present Value (NPV) of a Base Case Scenario. For our purposes the Base Case Scenario is defined as the wind park without electrolyser.

The NPV calculation and, therefore, the H$_2$ price calculation, includes the following terms:

- Installation CAPEX and OPEX.
- Storage system replacement costs (when within the period of study, the storage reaches its lifetime).

- Financial costs of the loan (related to the CAPEX of both the installation and the replacement installation).
- Energy sale incomes.
- Scenario related incomes (e.g. in case of secondary frequency service provision).
- Inflation and discount rate (timeframe parameters).
- Pending credits and residual value of the storage system at the end of the period of study.

In case of Smøla and Moncayuelo, the H_2 production costs don't include and are not affected by those pertaining to the storage and the compression stage since the corresponding integrated systems are not equipped with the tank and the fuel cell.

3.1   Raggovidda Wind Farm – Norway [3]

The Wind-H_2-FC system in Raggovidda will consist of the current 45MW wind farm, of the 2.5MW PEM electrolyser, the 64m^3 tank and the 120kW fuel cell, limited to 100kW due to regulatory constraints (Figure 5).
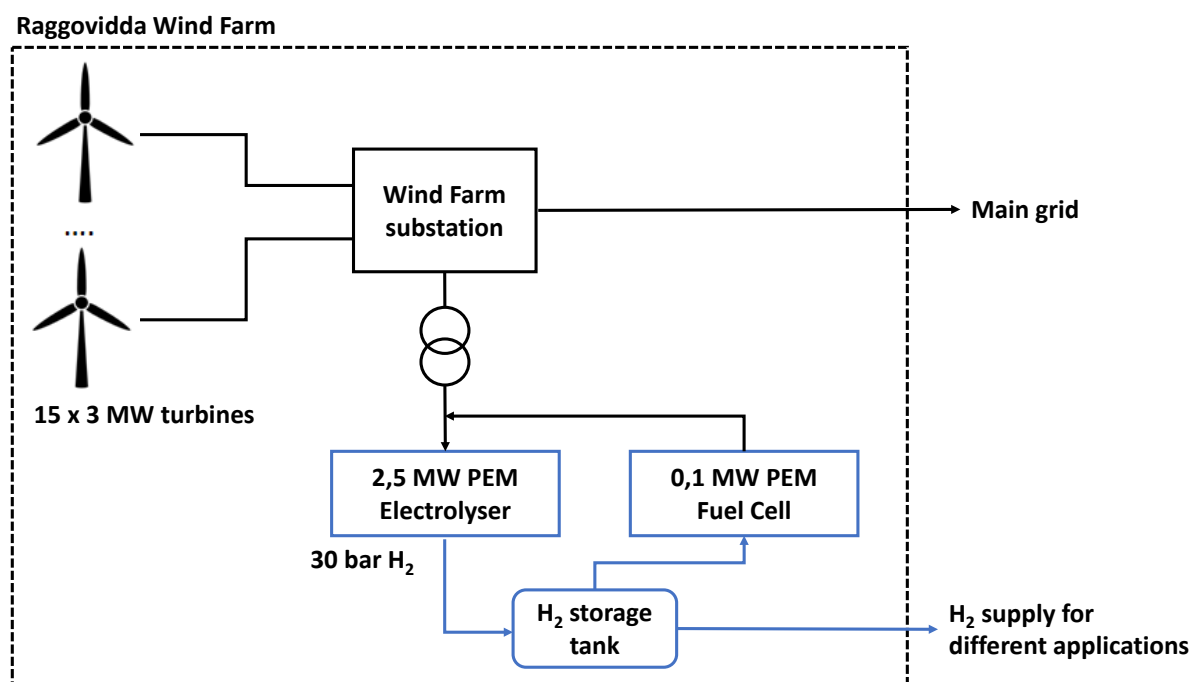
Figure 5. Conceptual layout of the Raggovidda Wind-H_2 system.

The electrolyser will generate H_2 at 30bar which in turn will be assumed to be stored at 300 bar in a tank (expected development beyond the Haeolus project). As there has not yet been established a specific use and a reference price for the H_2, the studies have not considered any income from the sale of the produced H_2, which indeed is re-electrified by the fuel cell.

3.1.1 Main features and costs

Table 6 summarises the general information of the Raggovidda wind farm provided by Varanger Kraft [11].

Table 6. General information of the wind farm.

Raggovidda wind farm	
Parameter	**Value**
Nominal power	45MW
Number of wind turbines	15
Turbine nominal power	3MW
Connection point export power	45MW
CAPEX	900€/kW
OPEX	40€/kW per year

The CAPEX and OPEX reported in Table 6 are estimates achieved by taking into account the current state of the art and the market data provided by Varanger Kraft and not the actual ones of the wind farm in Raggovidda. Further, the estimates have been obtained by considering as part of the CAPEX the cost per installed kW that includes all the incurred costs as civil works, turbine cost, deployment, electrical connection, engineering and permissions among others, and as part of the OPEX a fixed annual cost per installed kW that is increased yearly according to the estimated the inflation rate [12].

3.1.2 Wind farm production

Table 7 summarises the results from the statistical study of the real generation of the Raggovidda wind farm for 2015, 2016 and 2017. For each year maximum, minimum and mean power and the annual energy production are shown. As it can be seen, there is only a slight variation (<8%) in the annual generation from one year to another. Regarding the hourly generation profile, the histogram in Figure 6 shows that the statistical distribution is very similar for the three years.

Thus, considering that there are no relevant differences among the three years, 2017 data have been selected as reference for the techno-economic studies.

Table 7. Summary of Raggovidda wind farm generation 2015-2017.

Raggovidda wind farm Generation 2015-2017				
Year	**Max (MW)**	**Min (MW)**	**Mean (MW)**	**Generation (MWh)**
2015	45.35	0.00	22.46	196,781
2016	45.18	0.00	20.85	182,662
2017	45.03	0.00	21.78	190,762
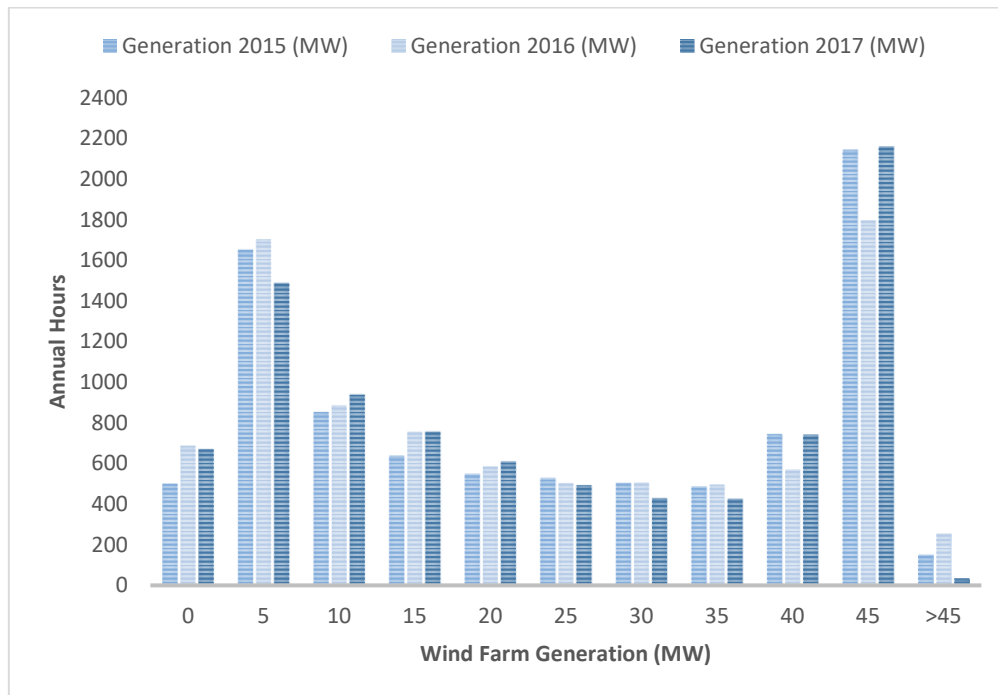
Figure 6. Histogram of Raggovidda Wind farm generation 2015-2017.

3.1.3   Remuneration of renewable energy production

The renewable energy produced by the Raggovidda wind farm has a remuneration scheme that includes several sources of revenues and some fees. Particularly, the relevant parameter to be considered is the electricity price that is determined as

$$\text{electricity price} = \text{spot market price} + \text{green certificate} + \text{guarantee} - \text{tariffs}.$$ *Equation 1*

The next subsections describe the terms of Equation 1 and the values that have been used for the simulations.

As mentioned in before, the reported studies do not take into account for any income from the sale of the produced H_2.

3.1.3.1   *Electricity spot market prices: real data for the POC of Raggovidda (Tromsø)*

Table 8 summarises the statistical data of the electricity spot market of the Point Of Connection (POC) of the Raggovidda wind farm (Tromsø) for 2015, 2016 and 2017. For each year maximum, minimum and mean prices are shown. As it can be seen in Table 8 there is a variation from one year to another regarding maximum and minimum values, whereas mean prices are quite similar. The price histogram reported in Figure 7 shows the statistical distribution of prices per year, and as it can be appreciated the most prevalent prices for the three years are in the range of 20€ to 35€.

Table 8. Electricity prices at Tromsø 2015-2017. Statistical Study.

Spot market prices at Tromsø 2015-2017			
Year	Max (€/MWh)	Min (€/MWh)	Mean (€/MWh)
2015	61.76	1.46	20.43
2016	214.25	11.28	25.06
2017	114.70	2.97	25.73
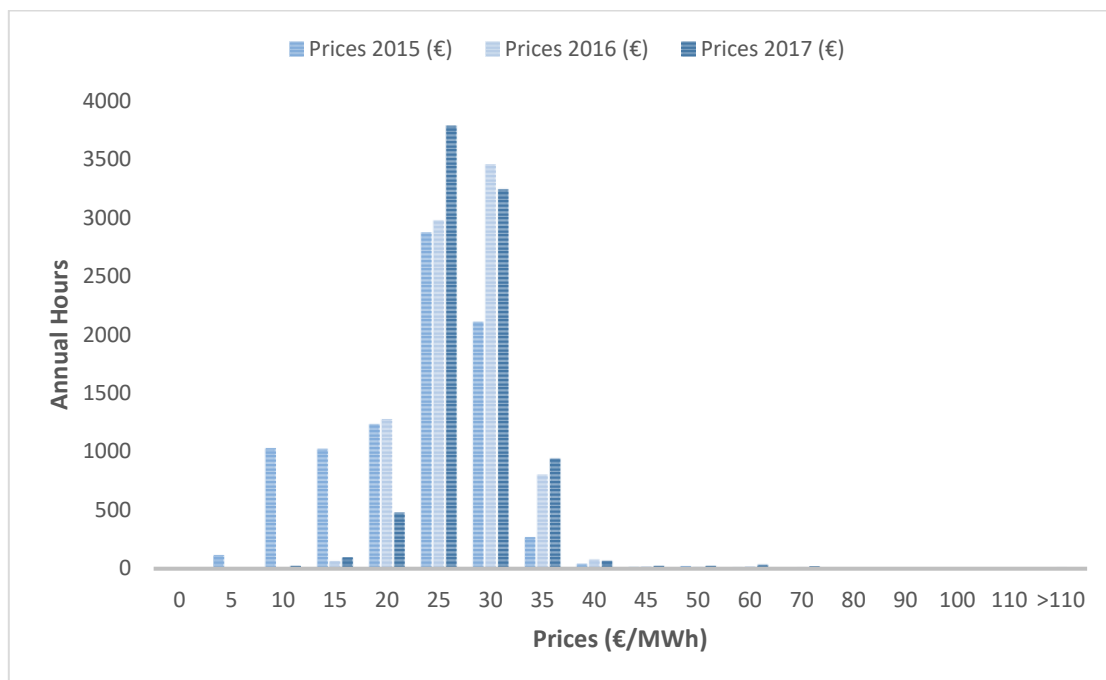
Figure 7. Histogram of spot market energy prices of 2015-2017.

As there are few differences among mean prices and the occurrences are also similar for the three years, 2017 data has been selected as reference.

3.1.3.2 Green certificate, guarantee and tariffs in Norway

Norway promotes renewable energy through a quota system including a certificate trading scheme. Grid operators are obliged to connect renewable energy plants to their grids without discriminating against certain (groups of) plant operators. This obligation also applies if the realisation of the new connection requires the development of the grid [13].

Since 1st January 2012, Norway and Sweden have had a joint market for electricity certificates. This is based on the Swedish electricity certificate market, which has existed since 2003.The goal of the two countries is to develop new energy production based on renewable energy sources amounting to 28.4TWh by the end of 2020. Sweden will finance 15.2TWh and Norway 13.2TWh. The market will determine when and where the new production will take place. This common green certificate market is a support scheme for renewable energy technology.

The value of the green certificate is variable and depends on the amount of energy injected into the grid. Another source of income for renewable energies is the one related to the green energy guarantee concept, that basically contributes with 1€ per MWh. On the other hand, there are also some fees or tariffs that are applied to the renewable energy production. These tariffs are related to two concepts:

Energy dependant tariff It is obtained as a percentage of the energy price. It is obtained on a variable percentage of energy process.

Fixed tariff Different fees are applied for producers and consumers.

As a summary, the income per MWh of renewable energy feed to the grid is as follows:

$$\text{wind energy income} \left(\frac{\text{€}}{\text{MWh}}\right) = \text{spotmarket price} + \text{green certificate} + \text{green Guarantee} - \text{tariff}_{\text{EnergyComponent}} - \text{tariff}_{\text{Fixed}}.$$

Equation 2

For this study, the average value of green certificates, guarantees and tariffs by year 2016 are used and reported in Table 9.

Table 9. Green certificate & tariff in Norway.

Green certificates and tariffs (year 2016)	
Parameter	**Value**
green certificate	15.45€/MWh
tariff$_{\text{EnergyComponent}}$	-4% spot market price
tariff$_{\text{Fixed}}$	-1.34€/MWh
green energy guarantee	1€/MWh

However, currently there is uncertainty on the future evolution of the green certificates and tariffs, that it could even end up with their elimination from 2021 [14]. To take this into account, a sensitivity analysis with respect to the green tariff component of the energy price has been carried out and the following values have been considered:

1. 100% of actual sum of green certificate, guarantees and tariff: 13.1€/MWh.
2. 50% of current value: 6.37€/MWh.
3. 25% of current value: 3€/MWh.
4. Green certificate & tariffs are not taken into account: 0€/MWh.

Same studies have been carried out just modifying the green tariff value in order to see how it impacts on the H$_2$ production cost.

3.2 Smøla Wind Farm – Norway

Smøla wind farm is located in Smøla Municipality, Moere og Romsdal County. The wind farm is situated in a flat and open terrain 10-40 metres above sea level. The wind farm was constructed in two steps. Firstly, 20 wind turbines 2MW each became operational in September 2002, then 48 wind turbines 2.3MW each were commissioned in September 2005 [15].

The Smøla Wind-H_2 system will consist of the 150MW Smøla wind farm and the 2.5MW PEM electrolyser (Figure 5). Since the system does not include a storage tank, the studies have been carried out by assuming unlimited storage capacity.

Smola Wind Farm
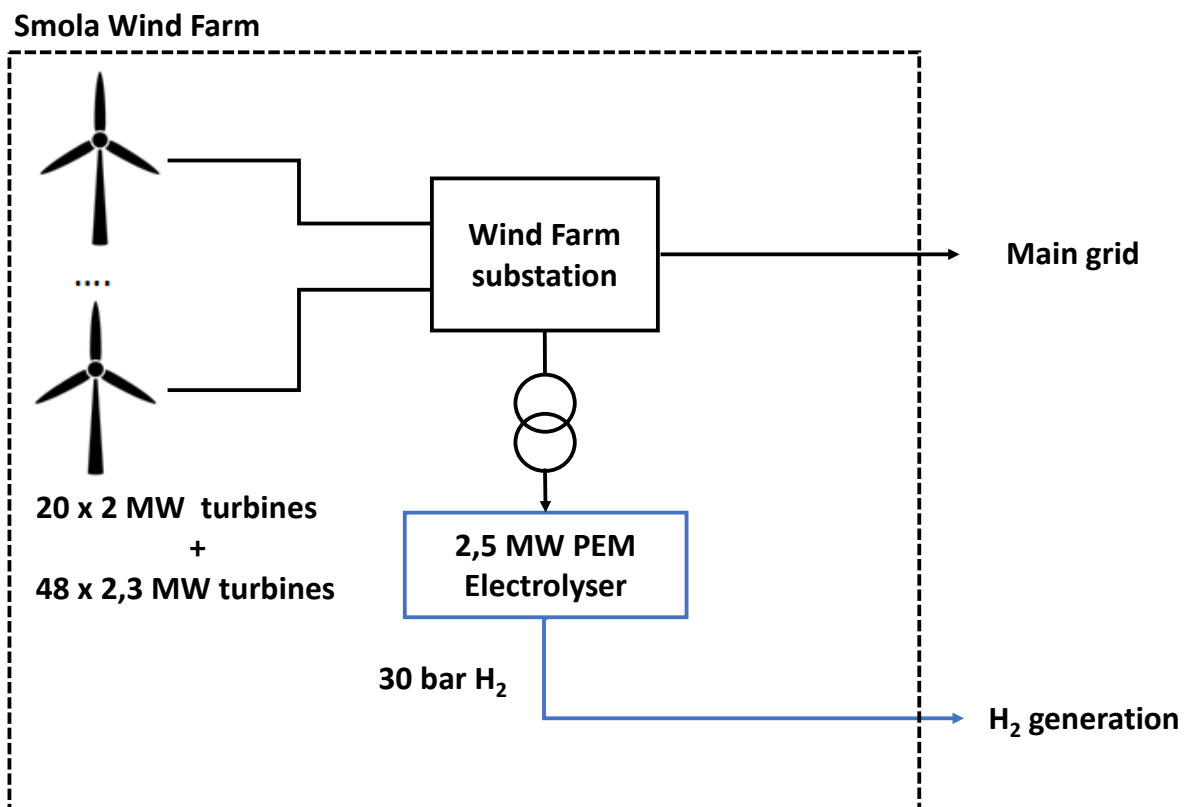
Figure 8. Conceptual layout of the Smøla Wind-H_2 system.

The electrolyser performance is studied considering operations under the "Optimal H_2 production" and the "Congestion management" scenarios, which are further described in section 4.6.

3.2.1   Main features and costs

Table 10 summarises some general information provided by Sintef regarding the Smøla wind farm.

Table 10. General information of the wind farm.

Smøla wind farm	
Parameter	**Value**
Nominal power	150MW
Number of wind turbines	68
Turbine nominal power	2-2.3MW
Connection point export power	45MW
CAPEX	900€/kW
OPEX	40€/kW per year

As for Raggovidda, the wind farm's CAPEX and OPEX reference values are not directly those of the Smøla wind farm, but they have been estimated according to the technology current state of the art.

The OPEX has been defined as a fix annual cost per installed kW. This cost has a yearly increase according to the inflation.

3.2.2   Wind farm production

Table 11 summarises the results from the statistical study of the real generation of the Smøla wind farm for 2015, 2016 & 2017. For each year maximum, minimum and mean power and the annual energy production are shown. As it can be seen, there is a significant variation (≈30%) in the annual generation from one year to another. Regarding the hourly generation profile, the histogram in Figure 9 shows the histogram of the hourly generation profile.

Table 11. Summary of Smøla wind farm generation 2015-2017.

Smøla wind farm Generation 2015-2017				
Year	**Max (MW)**	**Min (MW)**	**Mean (MW)**	**Generation (MWh)**
2015	148.59	0	45.73	400,638.76
2016	148.37	0	32.47	284,497.28
2017	148.45	0	40.93	358,574.74
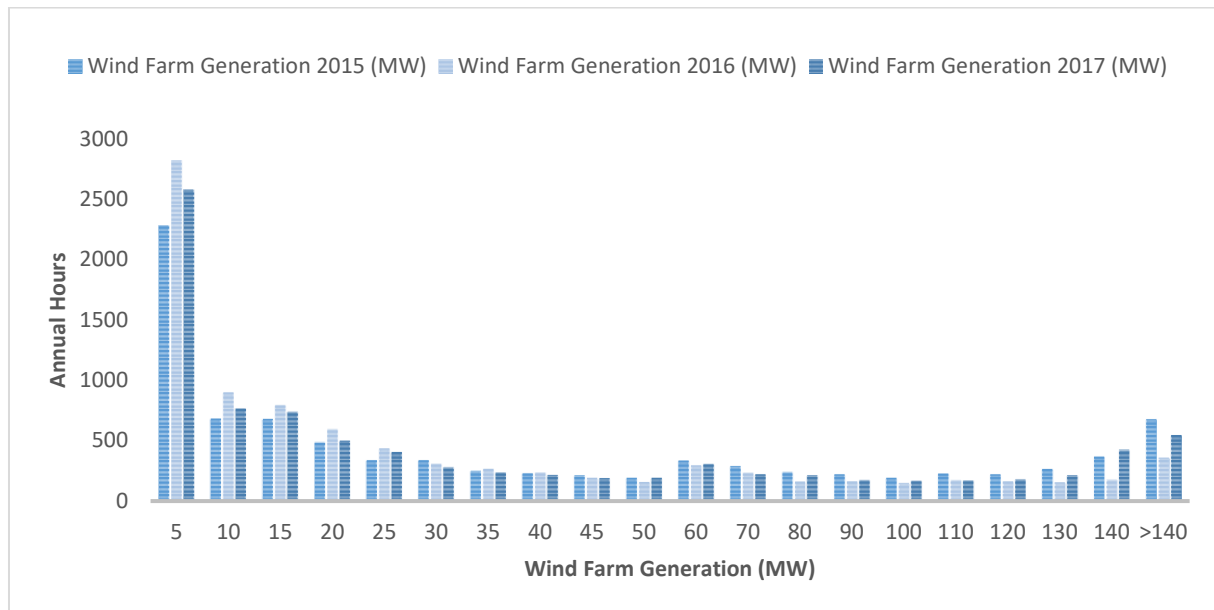
Figure 9. Histogram of Raggovidda wind farm generation 2015-2017.

Thus, depending on the year considered the obtained results will vary. With the aim of choosing a representative year, a statistical analysis of previous years has been carried out (Figure 10), since there are data available from 2008.
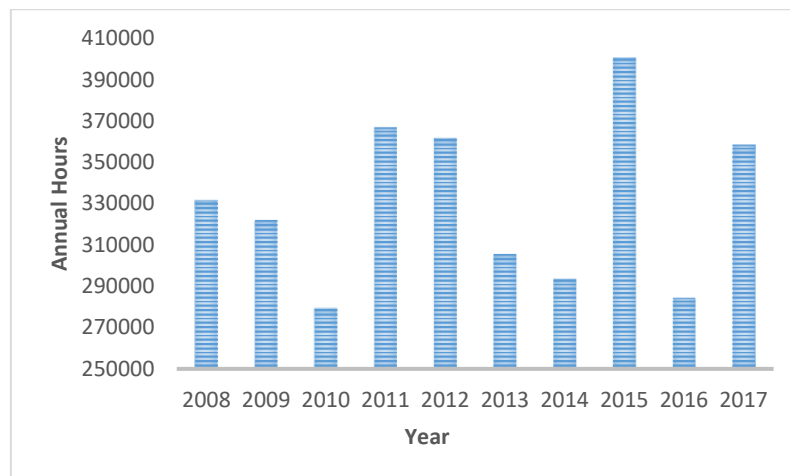
Figure 10. A statistical analysis of Raggovidda wind farm generation from 2008 to 2017.

Based on the results of these statistical study, data for 2017 have been used, since 2017 corresponds to a medium year in terms of energy and, in addition, is the most recent year.

3.2.3   Remuneration of renewable production

The renewable energy produced by the Smøla wind farm has the same remuneration scheme as Raggovidda (section 3.1.3).

3.3 Moncayuelo Wind Farm – Spain

The Moncayuelo wind farm is located in the municipality of Falces in Navarre, an Autonomous Community of Spain, and was installed in 2004. The wind farm consists of 32 turbines 1.5MW each, which results in 48MW of total installed power. The developer, the operator and the owner of the wind farm is Acciona Energia [16]. Figure 11 shows the conceptual layout of the Moncayuelo Wind-H_2 system. Similarly to Smøla, since the system in Moncayuelo is not equipped with a storage tank, the studies have been carried out by assuming unlimited storage capacity.

The electrolyser performances are studied considering operations under the "Optimal H_2 production" and the "Secondary frequency regulation" scenarios, which are further described in the section 4.6.
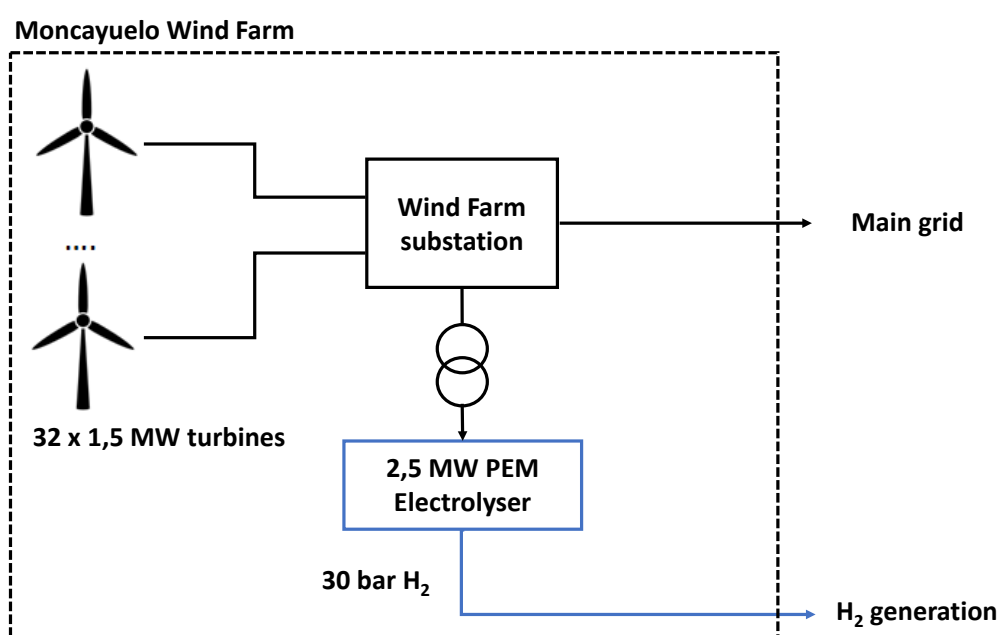
Figure 11. Conceptual layout of the Moncayuelo Wind-H_2 system.

3.3.1 Main features and costs

Table 12 summarises some general information provided by Acciona Energía [16] regarding the Moncayuelo wind farm.

Table 12. General information of the Moncayuelo wind farm.

Moncayuelo wind farm	
Parameter	**Value**
Nominal power	48MW
Number of turbines	32
Turbine nominal power	1.5MW
Connection point export power	48MW
CAPEX	900€/kW
OPEX	40€/kW per year

As for the Raggovidda and Smøla case studies, the wind farm's CAPEX and OPEX reference values are not directly those of the actual Raggovidda wind farm, but they have been estimated according to the technology current state of the art.

The OPEX has been defined as a fix annual cost per installed kW and increase yearly increase according to the inflation.

3.3.2 Wind farm production

In case of the Moncayuelo wind farm only production data for 2017 are available. Table 13 summarises the results from the statistical study of the real generation of the Moncayuelo wind farm for 2017. Maximum, minimum and mean power and the annual energy production are shown. Figure 12 shows the histogram of the wind farm generation.

Table 13. General information of the wind farm.

Moncayuelo wind farm Generation 2017				
Year	Max (MW)	Min (MW)	Mean (MW)	Generation (MWh)
2017	47.34x	0	16.60	145,384
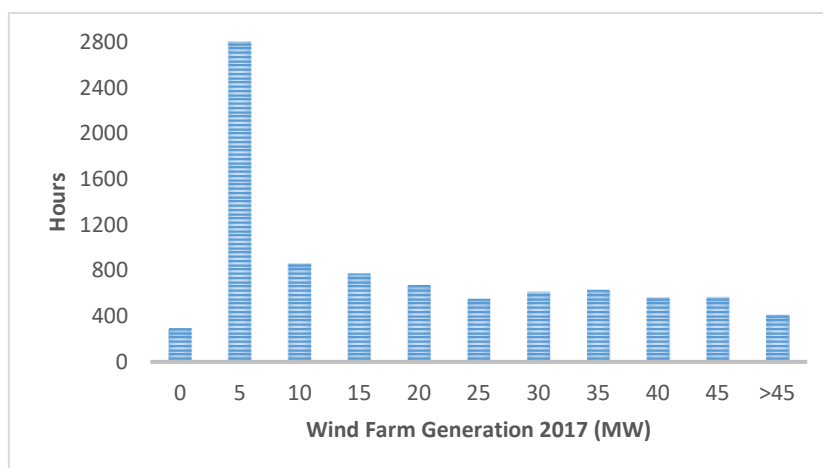
Figure 12. Histogram of Moncayuelo wind farm generation 2017.

3.3.3 Remuneration of renewable production

In the Moncayuelo case study, the considered remuneration scheme is fairly simple in comparison to those for the Raggovidda and Smøla ones. Here, the electricity price for calculating the incomes from the generated power is equal to the spot market price[3]. Table 14 summarises the statistical data of the electricity spot market for the Moncayuelo wind farm for 2018. Maximum, minimum and mean prices are shown. The data of year 2018 have been used as input for the simulations as the most recent.

As in Raggovida and Smøla case studies, the reported studies do not take into account for any income from the sale of the produced H_2.

---

[3] According to the present conditions of wind farms in the Spain the new wind farms do not receive additional remuneration for the generated power (https://www.renovablesverdes.com/subastas-renovables/; http://www.subastasrenovables.omie.es/files/boe-a-2017-8997.pdf).

Table 14. Spot Market Prices at Moncayuelo 2018.

Spot Market Prices at Moncayuelo 2018			
Year	Max (€/MWh)	Min (€/MWh)	Mean (€/MWh)
2018	84.13	2.06	57.29
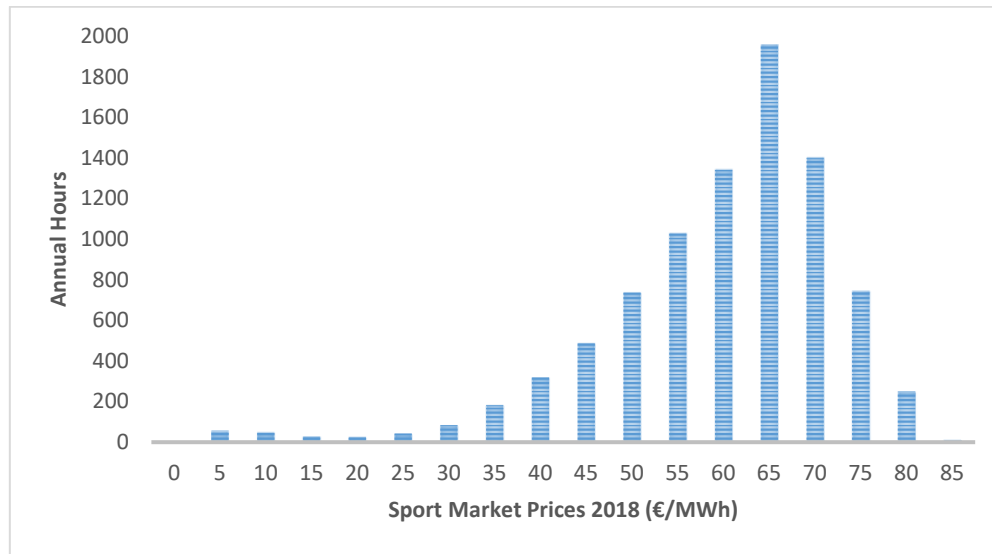
Figure 13. Histogram of Moncayuelo wind farm spot market prices 2018.

3.3.3.1   Secondary frequency: real data for the POC of Moncayuelo (ESIOS [18])

The secondary frequency regulation in Spain according to REE "is an optional ancillary service whose purpose is to maintain the generation-demand balance, correcting automatically deviations with respect to the anticipated power exchange schedule of the 'Spain' Control Block, and the system frequency deviations. Its temporary action horizon ranges from 20 seconds to 15 minutes. This service is remunerated by means of market mechanisms via two concepts: availability (control band) and usage (energy), downward/upward secondary reserve energy prices (€/MWh). It is equivalent to the European product known as aFRR - automatic Frequency Restoration Reserves" [2].

In case of the secondary frequency service provision, the TSO provides data about the secondary regulation service through its ESIOS [18] platform for all market periods (hourly, in this case). The data of year 2018 have been used as input for the simulations as the most recent.

Table 15. Spot Market Prices at Moncayuelo 2018.

Secondary frequency regulation prices 2018			
	Max	Min	Mean
Secondary reserve marginal price (€/MW)	100	3.5	12.55
Downward secondary reserve energy price (€/MWh)	180.3	0	49.28
Upward secondary reserve energy price (€/MWh)	180.3	0	53.02
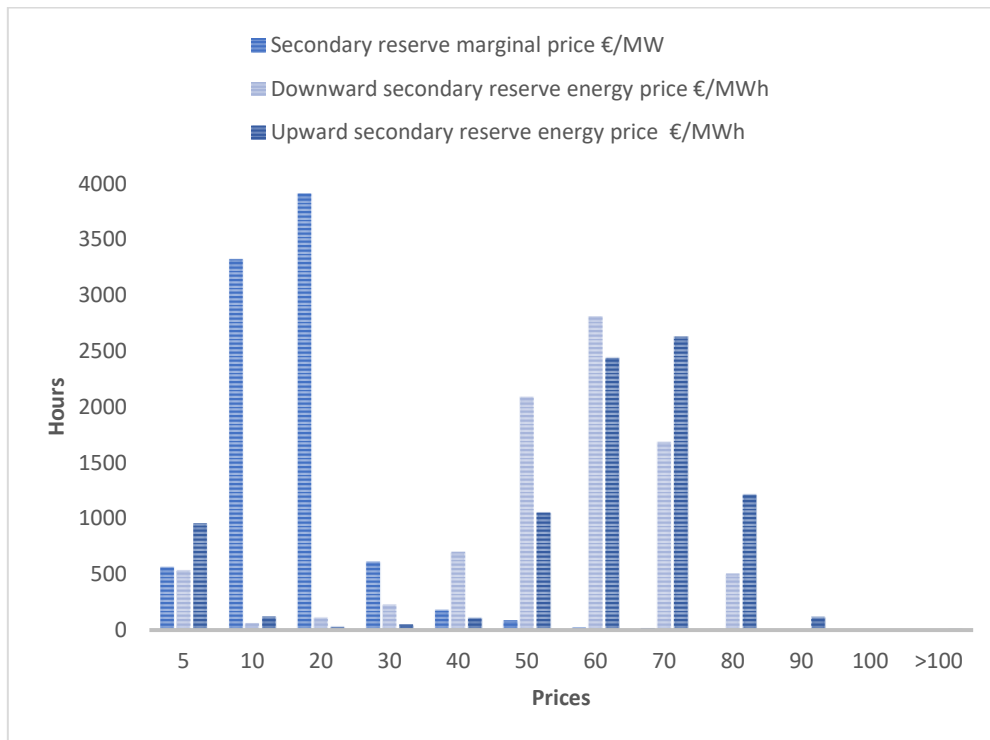
Figure 14. Histogram of Moncayuelo wind farm spot market prices 2018.

4 Application of the System Integration Design and Model

4.1 Methodology

The methodology followed for the techno-economic analysis of three scenarios consists of 5 major steps (as it can be seen in the flowchart shown in Figure 15 [3]):

Case study and simulation strategy definition The first step consists in defining which are the most relevant results to be calculated, i.e. the lowest LCOH2 and the associated Wind-H_2 system for each case study and scenario, and optimized and selecting the sensitivity parameters to be studied. For these studies the input data are

   a. Wind farm generation data series.
   b. Spot market energy price data series.
   c. Wind farm power connections point power restrictions.
   d. Secondary frequency regulation requirement and price data series (hourly).

Hydrogen system data Definition of the techno-economic parameters of the H_2 system, which are basically the data of the PEM electrolyser manufactured by Hydrogenics, the fuel cell, manufactured by Hydrogenics as well as part of the INGRID [10] EU cofounded project, and the storage tank. In the Raggovidda integrated system a 2.5MW electrolyser and a 120kW, limited by 100kW, fuel cell are considered. From a theoretical and optimization perspective in Smøla and Moncayuelo, other electrolyser sizes will be also considered, and the fuel cell and the storage tanks will be neglected.

Control Strategy definition The specific control strategy for the combined operations of the wind farm and the electrolyser must be defined and implemented in the simulation tool. Different control strategies can be applied for each scenario.

Simulation Simulations are carried out by a TECNALIA's proprietary tool, which is intended to the optimal sizing and operation of storage systems in combination with renewable energy sources (RES). This software has been adapted for working with hydrogen technologies and to analyse the mentioned scenarios.

Results analysis The analysis of results may require launching new simulations so that to optimize controls strategies. The results obtained in these analyses are valuable for the optimal design of wind hydrogen systems and for the development of control strategies.
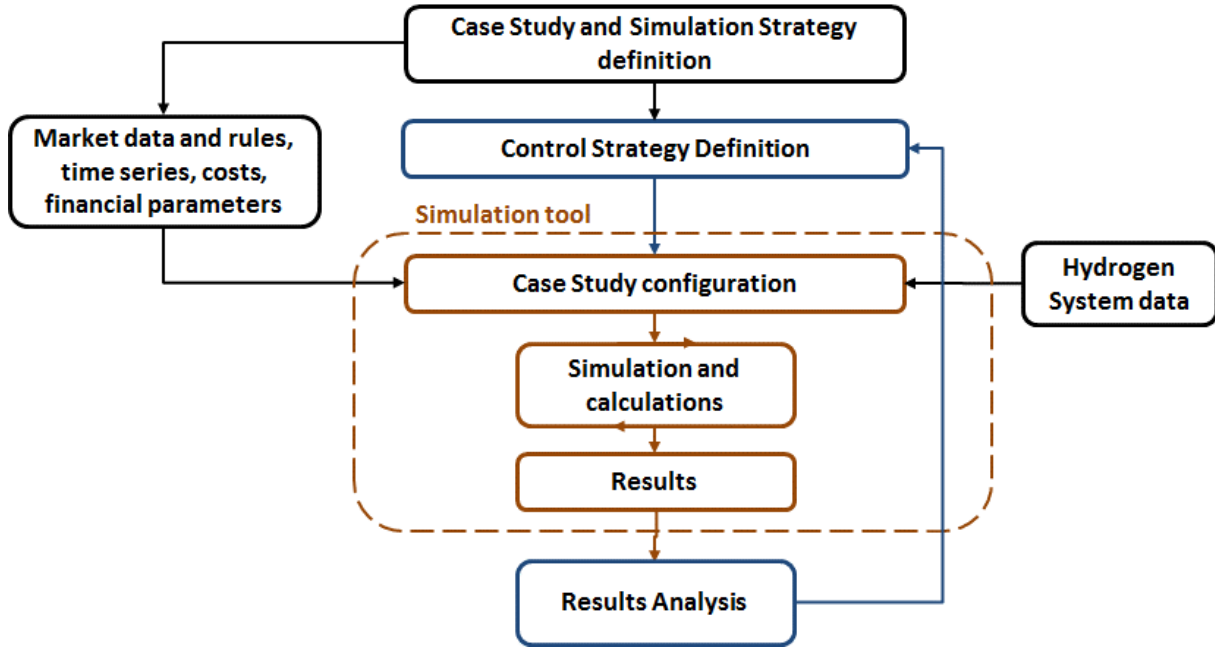
Figure 15. Techno-economic studies overall methodology [3].

4.2   Main Calculations

The techno-economic analysis basically pursues the optimization of the economic performance of Wind-H$_2$ system under different working conditions. Several parameters can be used for this purpose, as the NPV of the system or investment for a given period and the LCOE.

Regarding the NPV it can be defined as:

$$NPV = \sum_{i=0}^{n} \left[Income_i \cdot \left(\frac{1+e}{1+d}\right)^i - CAPEX_i \cdot \left(\frac{1}{1+d}\right)^i - OPEX_i \cdot \left(\frac{1+e}{1+d}\right)^i \right] + Remaining\ Value_n \cdot \left(\frac{1}{1+d}\right)^n,$$

Equation 3

where n is the analysis period in years, that in this study is set to 20 which is a typical choice for wind farms, e is the inflation rate, d is the discount rate, $Income$ is the sum of all the income sources of the wind H$_2$ system that depending on the scenario derive by the sale of energy[4] and by the sale of H$_2$[5], $CAPEX$ are the capital expenditures consisting of the wind farm and electrolyser investment costs, $OPEX$ are the operation and maintenance costs of both wind farm and electrolyser, and $Remaining\ Value$ is the remaining value of the investment at the end of the analysis period. It is important to consider the remaining value of the investment when the analysis period is below the useful life of an element.

However, as it has been previously mentioned, no income for the sale of H$_2$ have been considered. As a consequence, the NPV of a wind farm with an electrolyser is always smaller than that in the Base

---

[4] This is the only current source of revenues of the Raggovidda wind farm. The price per MWh fed to the grid is calculated according to remuneration scheme described in section 3.1.3.

[5] It has not been considered any income from sales of H$_2$, but the production cost was calculated.

Case Scenario. Considering this, the NPV or other economic parameters as the Investment Payback (IP) or Investment Rate of Return (IRR) are not the most representative ones for evaluating such a system. Thus, in our case the main economic parameter that can be evaluated and optimized is the Levelized Cost Of the produced H_2 (LCOH2). This parameter is a specific version for H_2 of the Levelized Cost of Energy (LCOE), which is a commonly-used metric to compare the costs of electricity from different energy sources. In this case the LCOH2 is an estimation of the price at which a unit of H_2 should be sold in order to recover the expenses and meet investors objectives.

The LCOE of a wind firm is usually defined as:

$$LCOE\left(\frac{€}{kWh}\right) = \frac{\sum_{i=0}^{n}\left[CAPEX_i \cdot \left(\frac{1}{1+d}\right)^i + OPEX_i \cdot \left(\frac{1+e}{1+d}\right)^i\right]}{\sum_{i=1}^{n} Energy\ production_i \cdot \left(\frac{1+e}{1+d}\right)^i},$$

Equation 4

where n is the analysis period in years, that in this study it has been fixed to 20 years which is the typical analysis period for a wind farm, e is the inflation rate, d is the discount rate, $CAPEX_i$ is the wind farm annual capital costs including debt cost for year i, $OPEX_i$ is the wind farm annual operation and maintenance costs for year i and $Energy\ production_i$ is the wind farm annual energy fed to the grid for year i.

The LCOH2 can be computed in two ways. Depending on the case study, both equations may not be equivalent. For example, when the cost of others element, such as the wind turbine, is directly assigned to H_2 productions cost the second option should be used.

Firstly, the LCOH2 can be calculated as the H_2 sale price that makes the NPV of the Wind-H_2 system equal to the NPV of the Base Case Scenario, then

$$LCOH2\left(\frac{€}{kg}\right) = \frac{NPV_{Base\ Case} - NPV_{Wind-H_2}}{\sum_{i=1}^{n} H_2 production_i \cdot \left(\frac{1+e}{1+d}\right)^i},$$

Equation 5

where $NPV_{Base\ Case}$ is the net present value of the Base Case Scenario and NPV_{Wind-H_2} is the net present value of the wind farm with electrolyser.

Secondly, the LCOH2 can be also calculated in same cases through the traditional LCOS formula adapted to the case of H_2:

$$LCOH2\left(\frac{€}{kg}\right) = \frac{\sum_{i=0}^{n}\left[CAPEX_i \cdot \left(\frac{1}{1+d}\right)^i + OPEX_i \cdot \left(\frac{1+e}{1+d}\right)^i + EnergyCost_i \cdot \left(\frac{1+e}{1+d}\right)^i\right]}{\sum_{i=1}^{n} H_2\ production_i \cdot \left(\frac{1+e}{1+d}\right)^i},$$

Equation 6

where $CAPEX_i$ is the electrolyser annual capital costs including debt cost for year i, $OPEX_i$ is the electrolyser annual operation and maintenance costs for year i, $H_2\ production_i$ is the amount of the produced H_2 per year for year i and $EnergyCost$ is the cost of the energy consumed for producing H_2. In practice, as the electrolyser will be installed inside the wind farm, for the techno-economic analysis it is not to be considered as a direct cost but as a loss of income since the energy consumed for the H_2 production is not fed to the grid.

4.3 Description of the Scenarios

As introduced in section 3, three scenarios have been considered and defined depending on the role of the electrolyser. In addition, a Base Case Scenario which consists in a wind farm without electrolyser has been also considered as a reference for determining the LCOH2. In the first scenario, namely Scenario 1, the electrolyser is operated for achieving optimal hydrogen production, in the second scenario, namely Scenario 2, the electrolyser is operated for achieving congestion management and in the third scenario, namely Scenario 3, the electrolyser is operated in order to provide secondary frequency regulation services. Then, depending on the specific case study, the representative scenarios have been considered in order to carry out the techno-economic analysis.

4.3.1 Base Case Scenario: wind farm without electrolyser [3]

As a first step, the economic performance of wind farms without electrolyser has been calculated. This is the Base Case Scenario where the H_2 production costs are obtained without any other component so that to be used as a benchmark for the economic performance of the Wind-H_2 system in each corresponding use case.

It is important to highlight that the Base Case Scenario depends on the wind farm's size. Hence, in principle it is different for each Case Study and may change from scenario to scenario for the same Case Study. If in an specific scenario the size of the wind farm is not fixed but it is part of the analysis, a different Base Case Scenario is used, for example in the congestion management scenario (see section 4.3.3)

4.3.2 Scenario 1. Optimal Hydrogen Production [3]

In this scenario the production of H_2 at the minimum possible cost by means of an electrolyser installed and operated within the wind farm is considered.

H_2 production costs have been calculated according to Equation 5 and take into consideration the cost of the consumed electricity (energy produced by the wind farm). In this scenario Equation 5 and Equation 6 are equivalent.

The electrolyser is operated according to the spot market electricity prices (see sections 3.1.3, 3.2.3 and 3.3.3), producing H_2 when the energy prices are below a certain threshold. The operation point, that is the production of the electrolyser, depends on the wind farm hourly generation:

1. if the wind farm's generated power for one hour is higher than the electrolyser's nominal power, the latter performs at full power;
2. if the wind farm's generated power for one hour is below the electrolyser's nominal power, but higher than its minimum operating power, all the energy is devoted to hydrogen production;
3. if the wind farm's generated power for one hour is below the minimum operating power of the electrolyser, the storage is not switched on.

The main purpose of scenario 1 is to enable the analysis of different operation strategies and to obtain the optimum values of the price thresholds that imply the lowest H_2 production costs. The objective of this scenario can be twofold:

1. production of a minimum of 120t in 2.5 years, as required by EU in the FCH-02-4-2017 topic;

2. optimization of H_2 production cost without limiting the H_2 production to the minimum required by the EU.

Two different operation strategies have been implemented:

1. *Fixed thresholds.* A fixed price threshold is defined and H_2 is produced only when the electricity cost drops below this limit. The selected value affects the number of yearly working hours of the electrolyser. Four different prices have been defined to determine the H_2 lowest production cost (≥120t- 2.5 years). The thresholds are fixed, and they have been selected to account for an arbitrary percentage of the yearly price values (Table 16). In addition, a fifth case is considered as reference, where the electrolyser operates for any electricity market price (the lower threshold exceeds the maximum yearly price). This is the case in which the electrolyser operating hours is maximum within the scenario.

Table 16. Wind farm price thresholds for optimal H_2 production (scenario 1).

	Moncayuelo Scenario 1: Optimal H_2 production thresholds
	% of values
UC1	3
UC2	10
UC3	25
UC4	35
UC5	100% below

For example, Use Case 1 (UC1) considers that, in the analysed year, the 3% of the hourly price values are below the lower threshold(dashed orange line), as can be observed in .
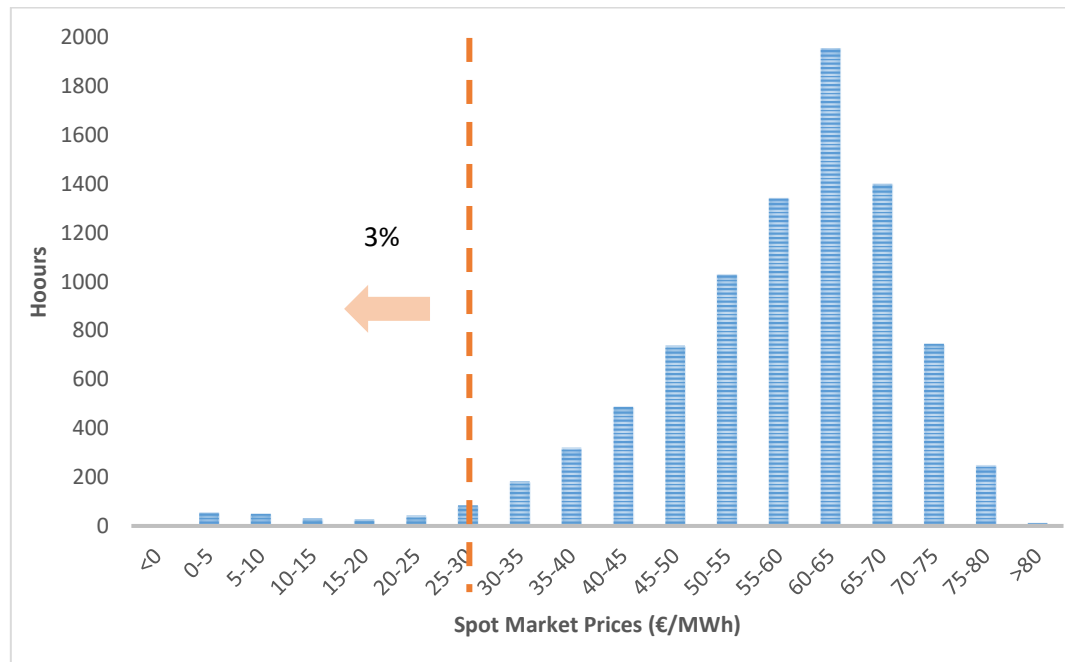
Figure 16. Moncayuelo. Scenario 1, UC1 low threshold (dashed orange line) and spot market prices histogram.

2. *Variable threshold.* The threshold changes from day to day so that the minimum H_2 amount (120tin 2.5years) is produced by operating the electrolyser 4 hours per day. This strategy could be consistent with a defined H_2 consumption rate and a limited capacity storage tank.

4.3.3   Scenario 2. Congestion Management [3]

In this scenario the electrolyser is operated for converting in H_2 the energy produced by the wind farm which is in excess with respect to the limits, either administrative of physical, at the connection point. That is, the electrolyser converts in H_2 energy that otherwise would be wasted.

Before carrying out the study, it is necessary to analyse which is the optimal size of the wind farm without electrolyser for a defined power export limit. In this case, as there is no electrolyser, when the production overpasses the export capacity, the wind production is curtailed. The solution that achieve the highest NPV will be considered as the optimal one, and the Base Case Scenario.

This study analyses Wind-H_2 solutions with different wind farms' and electrolyser's sizes, by comparing each corresponding LCOH2 calculated according to Equation 5. The cost is calculated to equal the NPV of the Wind-H_2 system to the Base Case Scenario which does not include the electrolyser.

In this case, since the H_2 is produced with energy that cannot be fed to the grid, the related production cost is zero and does not affect the LCOH2.

4.3.4 Scenario 3. Secondary Frequency Regulation

In this scenario the electrolyser is operated in order to provide secondary frequency regulation, as defined in the Spanish ancillary market [17]. The electrolyser, together with the wind farm, is operated accordingly. The secondary regulation service consists of several processes that are described, in general terms, below:

- *Allocation of the service:* during the generation programme definition process, in the day-ahead wholesale market, secondary frequency regulation reserves are settled. The Transmission System Operator (TSO) requests a regulation band for each area and a market period in the following day. Service providers offer their power increase and decrease capabilities together with a price (€/MWh). The TSO allocates the service considering capacity requirements and minimum costs for each of the periods.
- *Activation of the service:* if secondary regulation is effectively needed, a central control system calculates up or down deviations and sends control signals to allocate generators in an area, through an area control centre, which forwards the settings to the involved production or demand units. This is performed automatically by the AGC (Automatic Generation Control) systems.
- Two other processes related to this scenario are the measurement of the service providers response (identification of fulfilment or deviations in the band and energy request) and the payment for the service.

In the simulations performed for the current study, this scenario is considered in accordance to the following steps:

- The TSO provides data about the secondary regulation service through its ESIOS [18] platform for all market periods (hourly, in this case), that is the assigned band down (MW), the assigned band up (MW), the energy used down (MWh), the energy used up (MW), the band price (€/MWh), the energy price down (€/MWh) and the energy price up (€/MWh). The data for year 2018 have been used as input for the simulations.
- Even if both down and up requests take place within hourly market periods, the net energy request within each hour has been considered for the simulations. This requested net energy, which is a value for the whole Spanish peninsular system, is calculated as percentage of the requested band for that hour, depending on its sign (negative for down, positive for up). This percentage represents the requested energy to individual units by the AGC.
- The operation rate of the electrolyser, from its minimum to maximum defined power, is offered as secondary regulation capacity band for each hour. This total band is split in two, up and down bands, with the same power relationship between them as that requested for the whole system.
- Since the electrolyser is an electricity consumption device, in order to be able to provide up and down services, a central operation point is selected on day-ahead basis for the next day programme: within the day, in response to the AGC signal, consuming less would mean providing energy up, and consuming more than foreseen would provide energy down. See Figure 32 as example of the operation of a battery (some hours presented).
- The wind needs to produce a minimum power to proceed to place an offer for the secondary regulation service (10%). If this power is not reached, secondary service is not provided for that hour.

4.4 Raggovidda Wind Farm Case Study

This section analyses the coordinated operation of Raggovidda wind hydrogen (Wind-H$_2$-FC) system, defined in section 3.1. The results reported in this section are based on the study done in D5.1 [3]. The electrolyser performances are studied by operating it in compliance with Scenario 1. Optimal Hydrogen Production, where, based on the spot market energy prices, H$_2$ is produced when the price is below a certain threshold.

As concluded in [3] "*in practice, fix threshold strategy is easier to implement than the variable one as it is not necessary to continuously calculate the threshold value. However, the production of H$_2$ with the variable threshold strategy permits to produce H$_2$ in a constant and uniform way, which permits to optimize the size of the H$_2$ storage tank*". For the Raggovidda case the variable threshold has been implemented to assure the optimal use of the tank.

4.4.1 Base Case Scenario: wind farm without electrolyser [3]

The study related to Base Case Scenario for the Raggovidda Case Study has been done on the basis of 2017 production and 2018 market data for a 20 years period.

Table 17 and Table 16 summarise the Base Case Scenario configuration data and results. The LCOE has been obtained according to Equation 4. The results show that Raggovidda wind farm has a capacity factor of about 48%, which is higher than average values for onshore wind farms which typically are around 34% [19]. This high utilization factor permits to obtain very competitive LCOE and hence high NPV which in principle makes Raggovidda an outstanding location for wind farms.

Table 17. Raggovidda wind farm economic performance results.

Base Case Scenario: 45MW Raggovida wind farm	
Parameter	**Value**
Installed Power	45MW
Annual Generated Energy	190,805MWh
Mean power	21.77MW
Capacity factor	48.39%
CAPEX	40.5M€
Initial capital costs (40% of CAPEX)	16.2M€
Debt cost (real value)	30.2M€
Total (real value)	46.4M€
OPEX Annual	1.8M€
OPEX total (real value)	44.6M€
LCOE	23.12€/MWh

Table 18. Scenario 1. Raggovidda wind farm economic performance results for different green certificates.

	Base Case Scenario: 45MW Raggovidda wind farm			
	Green tariff 13.1€/MWh	Green tariff 6.37€/MWh	Green tariff 3€/MWh	Green tariff 0€/MWh
Annual Incomes	7,484,908€	6,200,791€	5,557,779€	4,985,364€
NPV	37.9M€	20.4M€	11.6M€	3.7M€

Regarding green certificates, as it can be seen in Table 18, they have a significant impact on the annual revenues from energy sales, being currently approximately the 33% of the incomes. Considering current spot market prices of electricity in Norway, green certificates are essential for the economic feasibility of wind farms, that is why the evolution of this value over next years may introduce a relevant uncertainty.

4.4.2 Scenario 1. Optimal Hydrogen Production with Variable Threshold

In this scenario the optimal H_2 production for Raggovidda Wind-H_2-FC is analysed when a variable threshold strategy is considered. The variable threshold is assumed to change from day to day so that the minimum H_2 amount (120t in 2.5 years) is produced by operating the electrolyser 4 hours per day.

Figure 17 shows the electrolyser operation strategy, the electricity spot market price, the variable price thresholds and the electrolyser activation. As it can be appreciated, the threshold varies daily and the electrolyser is activated when the price drops below the threshold. However, even if the electrolyser is supposed to work 4 hours each day, the electrolyser actually can work more or less hours. The reason why the electrolyser can work for more than 4h throughout the day is the way the variable threshold is implemented. Since the threshold is defined from day to day to obtain the best four hours (lowest prices), it can occur that in a day some hours have the same price, as on 29th September 2017. Regarding why the electrolyser works less than 4h, this can happen either because there is no wind or because the storage tank is full, as on 27th September 2017. As it can be observed, the electrolyser works either for consecutive or non-consecutive hours.
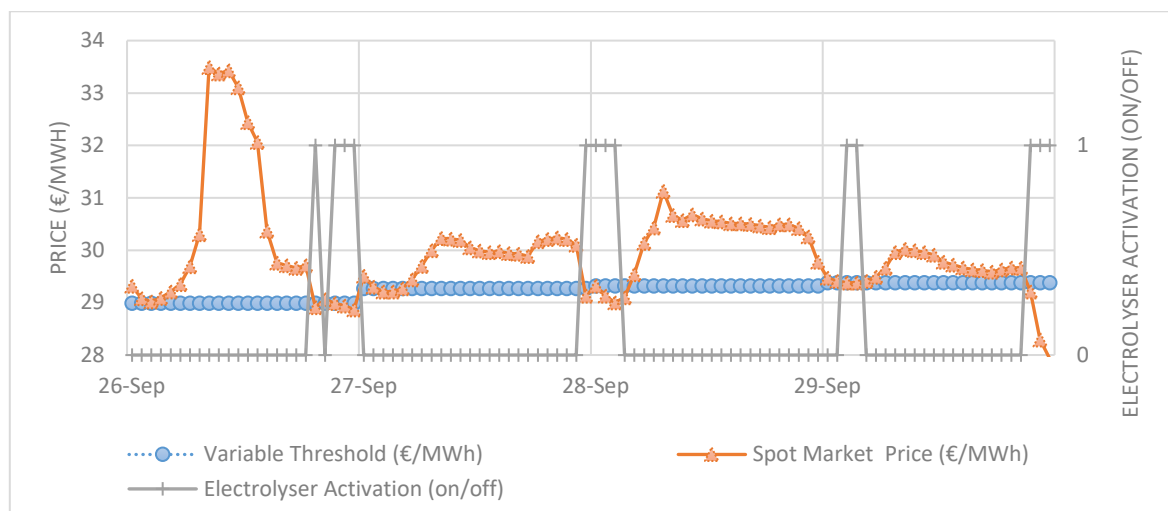
Figure 17. Market spot price (€/MWh) and electrolyser activation time profiles.

Figure 18 shows an example of the electrolyser performance in relation with the wind farm generated power and the electricity market price.
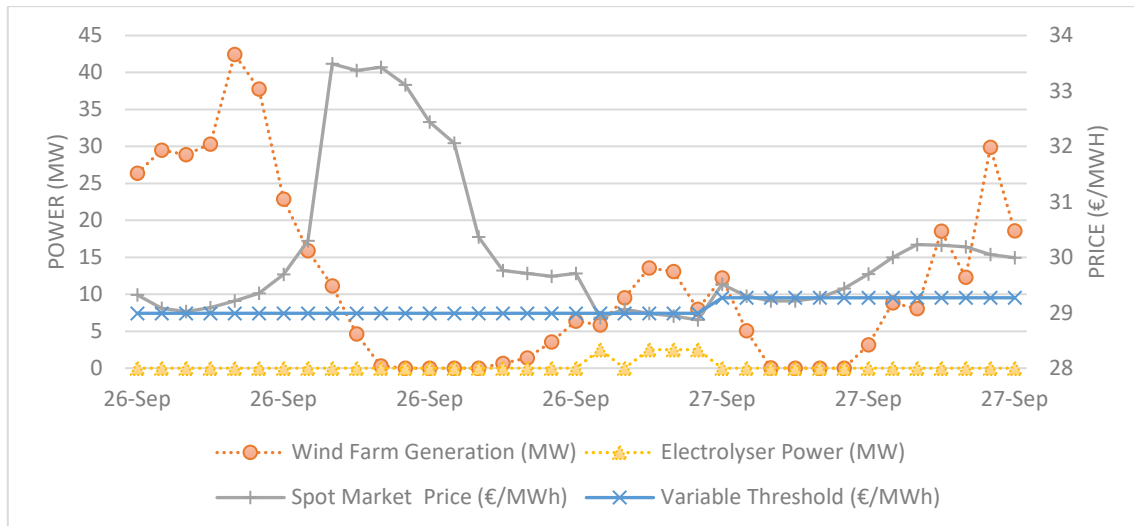
Figure 18. Raggovidda wind farm. Optimal H₂ production: electrolyser performance example.

For this Case Study the fuel cell operation strategy is also presented. Similar considerations will not be proposed for Smøla and Moncayuelo, because, as already mentioned, the fuel cell and the tank are not part of the corresponding integrated systems. Thus, regarding the Raggovidda plant, the fuel cell operation strategy is implemented with a twofold objective. On the one hand, electricity has to be generated according to a threshold sell price ideally greater than the threshold defined for the electrolyser, and, on the other hand, the SOC (State of Charge) of the tank has to be controlled. However, when the fuel cell is not able to re-electrify as much as H₂ is produced by the electrolyser in the same time, the tank fills up, and the electrolyser cannot generate until the tank's SOC reduces, which would jeopardize the project's main objective of achieving 120t in 2.5 years. Likewise, if the tank gets empty, the fuel cell cannot produce. In this sense, the main constraint is the size of the fuel cell, which is very small comparing to the size of the electrolyser. Therefore, the fuel cell, instead of working based on the threshold sell price, needs to operate whenever the electrolyser is not producing.

As mentioned, the LCOH2 (H₂ production cost) is used to compare the suitability of the study.

Table 19 shows the results obtained in the simulations for a 2.5MW electrolyser and a fuel cell of 100kW production. As it can be observed, when the variable operation strategy is implemented, that is the electrolyser works 4h a day, as long as there is wind, the tank is not full and the fuel cell works whenever the electrolyser is not generating, the production of H₂, within the 2.5 years, is slightly below the objective of the project (2.65%).

With the aim of obtaining a production of at least of 120t within the duration of the project, the fuel cell needs to work even when the electrolyser is producing.

Table 19. Smøla. Scenario 1 Results summary for a fix price threshold strategy of 255.1€/MWh, i.e. max. price (UC5) and several electrolyser sizes.

		Base Case	ELY:4h / FC: 20h	ELY:4h / FC: 20-24h
Wind farm data				
Installed Power (MW)		45	45	45
CAPEX (M€)		40.5	40.5	40.5
OPEX. Annual (M€)		1.8	1.8	1.8
Annual Generated Energy (GWh)		190.8	190.8	190.8
Electrolyser data				
Installed Power (MW)		--	2.5	2.5
CAPEX (M€)		--	3.32	3.32
OPEX. Annual (M€)		--	0.15	0.15
Annual/2.5y Generated H2 (t)		--	*47/116.81*	*49.6/124.19*
Working hours (h)		--	1,173	1,226
Fuel cell data				
Installed Power (MW)		--	0.120	0.120
CAPEX (M€)		--	0.270	0.270
OPEX. Annual (k€)		--	5.4	5.4
Annual Consumed H2 (t)		--	112.95	120.35
Working hours (h)		--	7,254	7,729
Integrated system data				
Annual injected energy (GWh)		190.8	188.9	188.7
Annual Incomes (M€)	**13.1**	7.48	7.46	7.46
	6.37	6.20	6.17	6.16
	3	5.55	5.52	5.51
	0	4.98	4.94	4.93
NPV (M€) for different green tariffs (€/MWh)	**13.1**	37.95	29.62	29.54
	6.37	20.38	12.22	12.15
	3	11.58	3.51	3.45
	0	3.7	-4.24	-4.29
LCOH2 (€/t) for different green tariffs (€/MWh)	**13.1**	--	13,020	12,359
	6.37	--	12,745	12,084
	3	--	12,608	11,946
	0	--	12,486	11,824

According to the simulations, the Wind-H$_2$-FC integrated system as defined in Raggovidda is not profitable, especially due to the reduced size of the fuel cell which affects the operation of both the fuel cell itself and the electrolyser, not allowing optimal control strategies to practically achieve good enough performances.

4.4.3 Conclusions

From the obtained results it can be concluded the Wind-H_2-FC integrated system is not economically feasible to produce H_2 for re-electrification since the obtained H_2 production costs, in the range of 11 to 13k€/t, are not competitive according to the current state of the art which are about 6k€/t [6].

There are several reasons why re-electrification in Raggovidda is not profitable. The efficiency of the H_2 re-electrification process is very low, around 30% in the best case. Apart the efficiency of the whole system, the size of the fuel cell is a key constraint. Even if the H_2 could be sold to avoid filling the tank the obtained LCOH2 wouldn't be enough to be competitive. As mentioned, to reach the objective of H_2 production of 120t in 2.5 years the fuel cell needs to be working around the 88% of the time, this limits the optimal H_2 production capacity of the whole system since the fuel cell will very likely produce in case of low energy prices.

4.5 Smøla Case Study

The objective of this study is to assess the expected H_2 generation of a wind park in Smøla, which characteristics were introduced in section 3.2. The electrolyser performances are studied by operating it in compliance with Scenario 1. Optimal Hydrogen Production and with Scenario 2. Congestions Management. For each scenario, several use cases are presented, mainly related to various electrolyser sizes.

4.5.1 Base Case Scenario: wind farm without electrolyser

The study related to the Base Case Scenario for the Smøla Case Study has been done on the basis of 2017 production and 2018 market data for a 20 years period. Table 20 and Table 21 summarise the Base Case Scenario configuration data and results. In this case, the LCOE has been obtained according to Equation 4.

Table 20. Smøla wind farm economic performance results.

Base Case Scenario: 150MW Smøla wind farm	
Parameter	**Value**
Installed Power	150MW
Annual Generated Energy	358,575MWh
Mean power	40.93MW
Capacity factor	27.28%
CAPEX	135M€
Initial capital costs (40% of CAPEX)	54M€
Debt cost (real value)	100,7M€
Total (real value)	154,7M€
OPEX Annual	6M€
OPEX total (real value)	148,7M€
LCOE	41.02€/MWh

---

[6] *"Green hydrogen — produced by electrolysis (splitting water molecules into hydrogen and oxygen) inside machines called electrolysers — today costs roughly $6/kg."* https://www.rechargenews.com/transition/green-hydrogen-cheaper-than-unabated-fossil-fuel-h2-by-2030-hydrogen-council/2-1-741658

Base Case Scenario: 150MW Smøla wind farm				

Table 21. Smøla wind farm economic performance results for different green certificates. Base Case Scenario.

	Base Case Scenario: 150MW Smøla wind farm			
	Green tariff 13.1€/MWh	Green tariff 6.37€/MWh	Green tariff 3€/MWh	Green tariff 0€/MWh
Annual Incomes (M€)	20.03	17.62	16.41	15.34
NPV (M€)	60.28	27.25	10.71	-4.00

The results show that Smøla wind farm has a capacity factor of about 28%, which is smaller than average values for onshore wind farms that are around 34% [19].

As it can be seen in Table 21, green certificates have a significant impact on the annual revenues from energy sales, concurring at approximately the 23% of the incomes in case of 13.1€/MWh green tariffs. Considering current spot market prices of electricity in Norway, green certificates are essential for the economic feasibility of wind farms, that is why the evolution of this value over next years may introduce a relevant uncertainty.

4.5.2 Optimal Hydrogen production. Scenario 1

In this scenario the optimal H_2 production for Smøla wind farm is analysed when a fixed threshold strategy is used. In Table 22 price thresholds are shown for each of the use cases explained in section 4.3.2.

Table 22. Smøla wind farm. Fixed thresholds for optimal H_2 production (Scenario 1).

Smøla: optimal H_2 production thresholds. Scenario 1		
	Price (€/MWh)	% of values
UC1	26.71	3
UC2	31.55	10
UC3	38.05	25
UC4	40.95	35
UC5	255.1	100% below

In Figure 19 an example of the electrolyser performance in relation with the wind farm generated power and the electricity market price is shown.
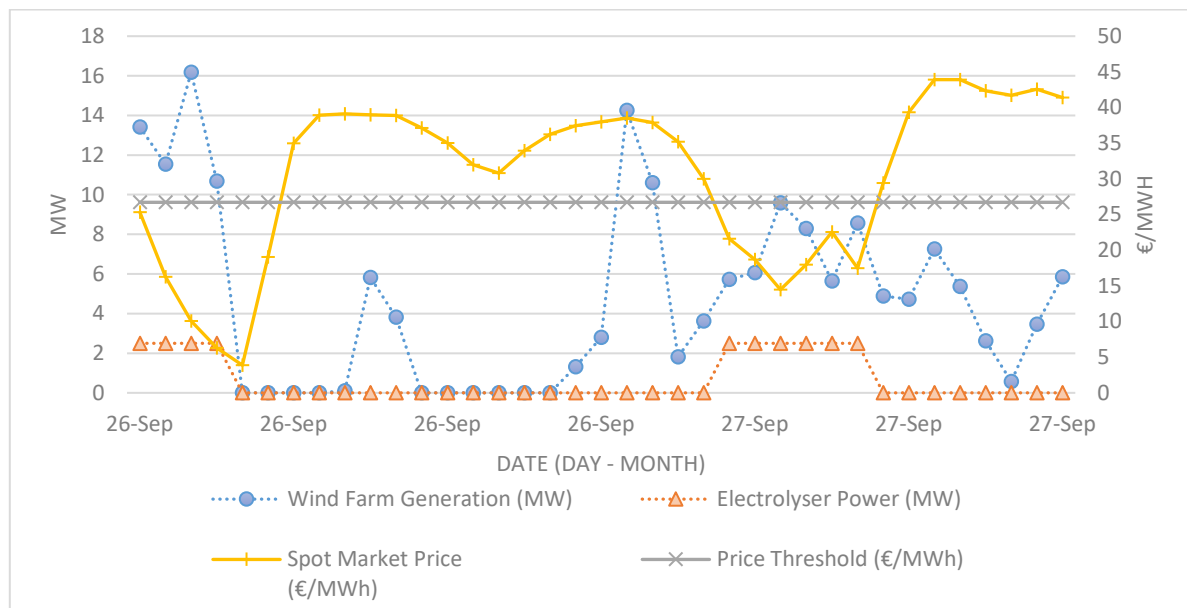
Figure 19. Smøla wind farm. Optimal H₂ production: UC1, 2.5MW electrolyser performance example.

As mentioned, the LCOH2 is used to compare the feasibility of the different solutions (use cases 1 to 5). Table 23 shows the results obtained in the simulations for a 2.5MW electrolyser.

Table 23. Smøla. Scenario 1 Results summary for fix price threshold strategies.

		Base Case	UC1	UC2	UC3	UC4	UC5
Wind farm data							
Installed Power (MW)		150	150	150	150	150	150
CAPEX (M€)		135	135	135	135	135	135
OPEX. Annual (M€)		6	6	6	6	6	6
Annual Generated Energy (GWh)		358.57	358.57	358.57	358.57	358.57	358.57
Scenario data							
Price threshold (€/MWh)		--	26.71	31.55	38.05	40.98	Max Price
Electrolyser data							
Installed Power (MW)		--	2.5	2.5	2.5	2.5	2.5
CAPEX (M€)		--	3.32	3.32	3.32	3.32	3.32
OPEX. Annual (M€)		--	0.15	0.15	0.15	0.15	0.15
Annual Generated H2 (t)		--	11	34	84	116	329
Working hours (h)		--	242	770	1,887	2,613	7,39
Integrated system data							
Annual injected energy (GWh)		358.57	357.98	356.72	354.06	352.33	340.93
Annual Incomes (M€) for different green tariffs (€/MWh)	**13.1**	15.34	20.11	20.06	19.93	19.83	19.12
	6.37		17.65	17.60	17.49	17.41	16.78
	3		16.42	16.38	16.28	16.20	15.60
	0		15.33	15.29	15.19	15,13	14.56

NPV (M€) for different green tariffs (€/MWh)	**13.1**	60.278	55.043	54.341	52.66	51.254	41.05
	6.37	27.25	22.07	21.48	20.05	18.80	9.655
	3	10.71	5.56	5.03	3.72	2.55	-60.69
	0	-4.00	-9.13	-9.61	-108.15	-11.91	-20.06
LCOH2 (€/t) for different green tariffs (€/MWh)	**13.1**	--	34,933	12,583	6,620	5,669	4,272
	6.37		34,457	12,222	6,258	5,308	3,911
	3		34,391	12,041	6,078	5,127	3,730
	0		34,229	11,880	5,917	4,966	3,569

According to the simulation results, the best option is to produce and sell as much hydrogen as possible to get the best NPV values. When the hydrogen is produced at higher market price, the hydrogen production cost can be considered higher. However, this is not strictly true, since the cost of producing the energy is the same. Actually, as can be seen in UC5, less energy is sold to the market at high prices and, therefore, the energy incomes reduce. This, together with overhaul costs related to the need of replacing the stack, reduces the NPV of the whole system as it is clear from UC4 and UC5. Even so, the bigger generated amount of hydrogen and the fact the overhaul costs are smaller than the CAPEX compensate this drawback and the LCOH2 reduces with the increase of working hours of the electrolyser.

Similar simulations have been performed for different electrolyser sizes. Table 24 shows the influence of the nominal power of the electrolyser in UC5 (analogous relationships are observed for the rest of use cases). In this case, the investment of the plant provides lower profitability with the increase of the electrolyser size. This is clear because the CAPEX and the OPEX increase, while the incomes for the sale of electricity reduce. However, here the LCOH2 is also lower when the use of the electrolyser is higher, that is, when the electrolyser works more hours.

Table 24. Smøla. Scenario 1 Results summary for a fix price threshold strategy of 255.1€/MWh, i.e. max. price (UC5) and several electrolyser sizes.

	Base Case	UC5 2.5MW ELY	UC5 5MW ELY	UC5 7.5MW ELY	UC5 10MW ELY	UC5 12.5MW ELY
Wind farm data						
Installed Power (MW)	150	150	150	150	150	150
CAPEX (M€)	135	135	135	135	135	135
OPEX. Annual (M€)	6	6	6	6	6	6
Annual Generated Energy (GWh)	358.57	358.57	358.57	358.57	358.57	358.57
Scenario data						
Low price operation threshold (€/MWh)	--	Max Price	Max Price	Max Price	Max Price	Max Price
Electrolyser data						
Installed Power (MW)	--	*2.5*	*5*	*7.5*	*10*	*12.5*
CAPEX (M€)	--	3.32	6.64	9.96	13.28	16.6
OPEX. Annual (M€)	--	0.15	0.3	0.45	0.6	0.75

Annual Generated H2 (t)		--	329	629	907	990	990
Working hours (h)		--	7,390	7,303	7,197	6,080	5,050
Integrated system data							
Annual injected energy (GWh)		358.57	340.93	324.88	310.02	305.70	305.81
Annual Incomes (M€) for different green tariffs (€/MWh)	13.1	15.34	19.12	18.20	17.36	17.18	17.19
	6.37		16.78	15.97	15.23	15.08	15.09
	3		15.61	14.86	14.16	14.03	14.04
	0		14.56	13.86	13.21	13.09	13.11
NPV (M€) for different green tariffs (€/MWh)	13.1	60.27	41.05	23.04	6.03	-1.69	-6.27
	6.37	27.25	9.65	-6.87	-22.51	-29.85	-34.44
	3	10.71	-6.06	-21.86	-36.81	-43.95	-48.54
	0	-4.00	-20.06	-35.20	-49.54	-56.50	-61.10
LCOH2 (€/t) for different green tariffs (€/MWh)	13.1	--	4,272	4,326	4,368	4,574	4,913
	6.37		3,911	3,965	4,008	4,215	4,554
	3		3,730	3,785	3.827	4,035	4,374
	0		3,569	3,625	3,669	3,875	4,214
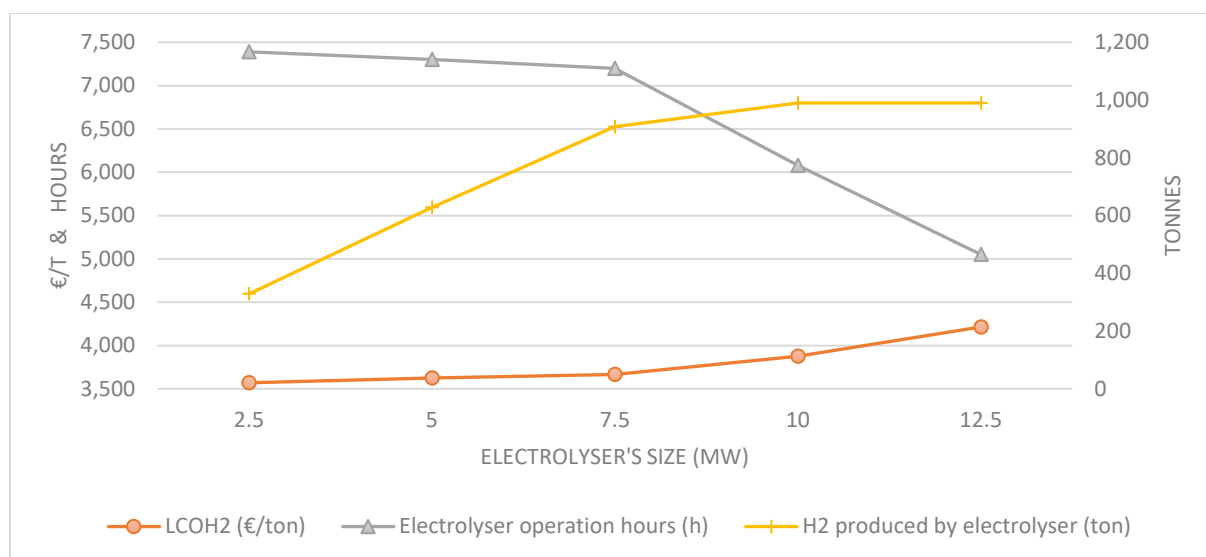
Figure 20. Smøla. Scenario 1, simulation results for UC5 and 0€/MWh green tariff: LCOH2, working hours, produced H₂.

It has to be mentioned that UC5 is not really an optimal H₂ production case, since the electrolyser operates all available hours independently of the price. Nevertheless, this shows that the profitability depends on the usage, as can be seen in Figure 21 and Figure 22.

The following graph shows the LCOH2 for all the analysed cases. In Figure 21 the LCOH2 for different electrolyser sizes and different fixed thresholds are shown. In this case a green tariff of 13.1€/MWh has been considered. The best solution is the one with an electrolyser of the smallest size.
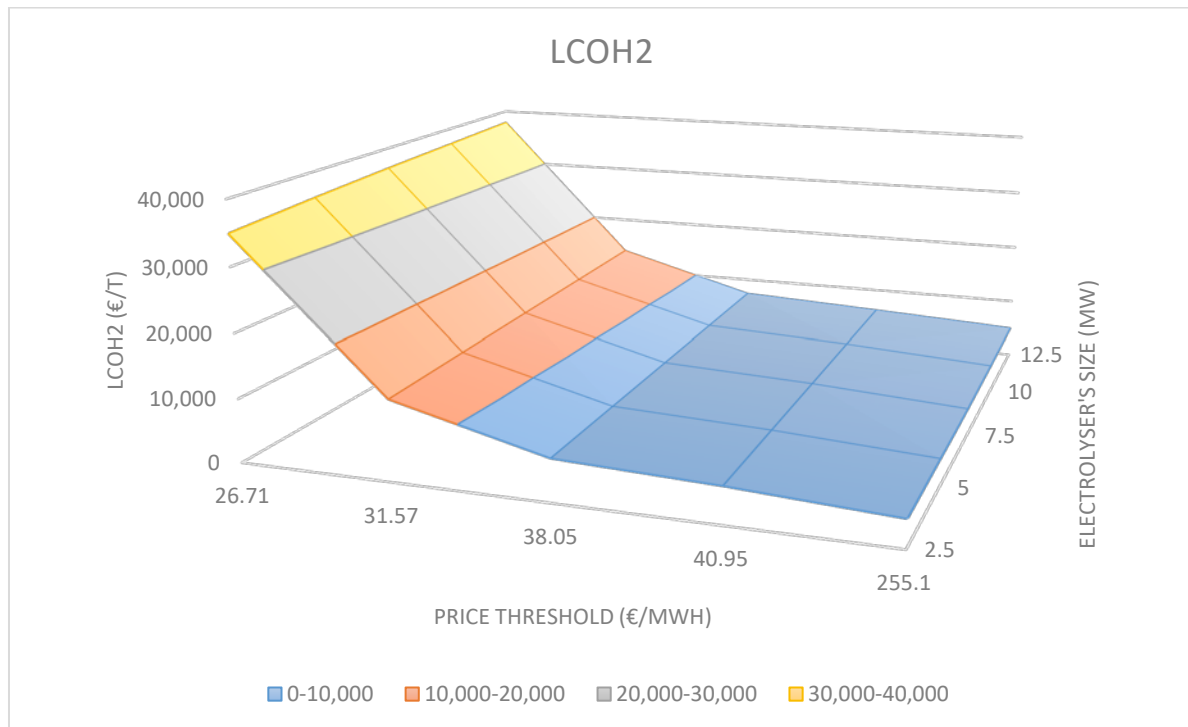
Figure 21. Smøla. Scenario 1, LCOH2 for different electrolyser sizes.

Figure 22 shows the influence of the green tariffs in the LCOH2 for the 2.5MW electrolyser. The LCOH2 price increases as the green tariff increases. In the best case, when the electrolyser works all available hours, for a green tariff of 13.1€/MWh the LCOH2 is up to 19% higher than the price when the green tariff is 0€/MWh.
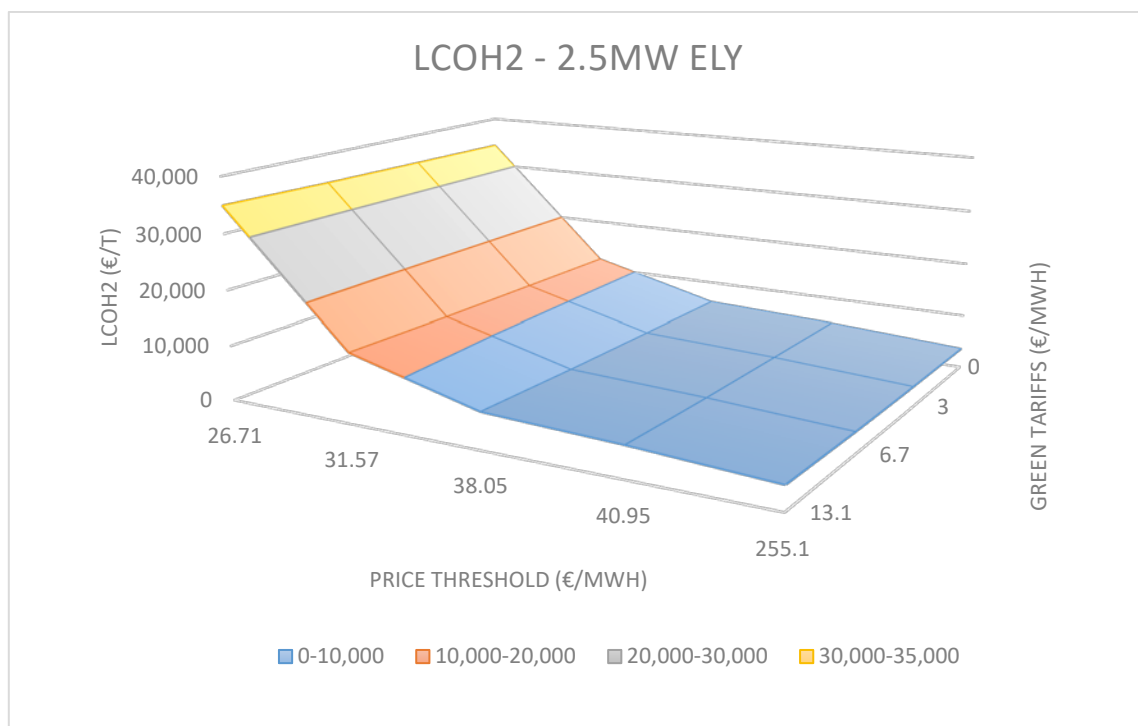
Figure 22. Smøla. Scenario 1, LCOH2 for a 2.5 MW electrolyser and different green tariffs.

4.5.3   Congestions Management. Scenario 2

As explained in section 4.3.3, this scenario basically consists in producing H_2 when the wind farm production overpasses the power connection point limit, either administrative of physical. Thus, the electrolyser produces H_2 with energy that otherwise would be wasted. The results have been achieved by taking into account an export limit of 150MW which is the wind farm's installed power.

4.5.3.1   Analysis of optimal wind farm size

Firstly, it has been analysed which is the optimal size of the wind farm without electrolyser and with a 150MW export limit. In this case as there is no electrolyser, when the production overpasses the export capacity the wind production is curtailed. The solution that achieves the higher NPV has been considered as the optimal one.

Table 25 summarises the results obtained for several wind farm sizes. As it can be seen, for current RES remuneration scheme, a wind farm of 160MW would be the one with highest NPV. The 90% of the additional generated power is fed to the grid while the other 10% is curtailed. This ratio justifies the additional investment in the wind farm, however for the case of higher power wind farm this ratio worsens and hence the additional investment is not profitable. This wind farm will be considered as the Base Case Scenario for Wind-H_2 solutions evaluation in Smøla.

Table 25. Results of Smøla wind farm sizing with 150MW export restriction.

Base Case Scenario: Smøla wind farm size with 150MW export restriction							
Installed Power (MW)		150	152.5	155	157.5	160	162.5
CAPEX (M€)		135	137.25	139.5	141.75	144	146.25
OPEX, Annual (M€)		6	6.1	6.2	6.3	6.4	6.5
Annual Generated Energy (MWh)		358,575	364,551	370,527	376,503	382,480	388,456
Annual Grid Injected Energy (MWh)		358,575	364,498	370,071	375,265	380,157	384,744
Annual Energy Curtailment (MWh)		0	53	457	1,238	2,322	3,712
Green certificates	**Annual Incomes (M€)**	20.03	20.37	20.68	20.97	21.24	21.49
13.1€/MWh	**NPV (M€)**	60.28	61.24	61.94	62.36	62.58	62.57
Green certificates	**Annual Incomes (M€)**	17.62	17.91	18.18	18.44	18.68	18.91
6.37€/MWh	**NPV (M€)**	27.25	27.67	27.85	27.80	27.56	27.13
Green certificates	**Annual Incomes (M€)**	16.41	16.68	16.94	17.17	17.40	17.61
3€/MWh	**NPV (M€)**	10.72	10.86	10.78	10.49	10.03	9.39
Green certificates	**Annual Incomes (M€)**	15.34	15.59	15.83	16.05	16.26	16.45
0€/MWh	**NPV (M€)**	-4.01	-4.10	-4.41	-4.91	-5.58	-6.41

Figure 23 shows the NPV for the analysed configurations depending on the considered green tariff. It can be observed how the energy price affects the profitability of the wind farm and hence its optimal size. Thus, for the case when green tariff is not considered, i.e. 0€/MWh, it does not make sense to increase the wind farm size over the export limit.
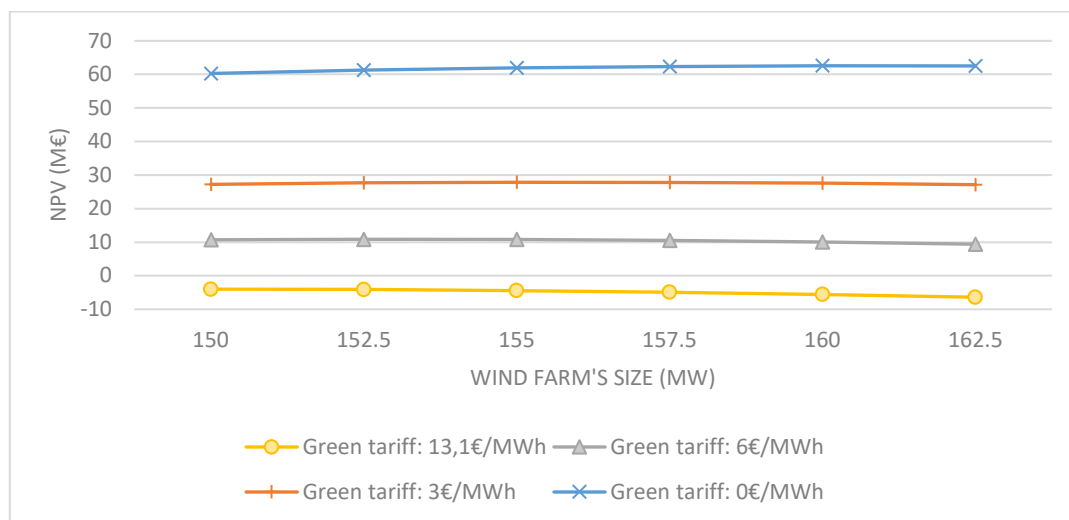
Figure 23. Base Case Scenario: NPV of the Smøla wind farm for different sizes and green tariffs (M€).

Figure 24 shows the NPV for the case of actual green tariff, i.e. 13.1€/MWh.
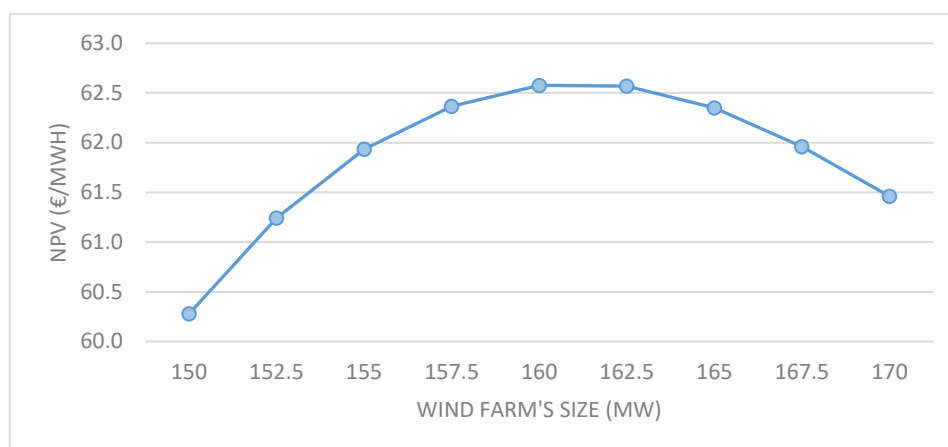
Figure 24. NPV for several Smøla wind farm sizes for 150MW export restriction.

4.5.3.2   Optimal wind-hydrogen system to reduce H_2 production cost

This study evaluates the use of the curtailed energy to produce H_2, analysing which is the optimal wind farm and electrolyser combination in terms of H_2 production costs. The H_2 production has not been limited either by the storage capacity or by the H_2 market demand. The definition of these aspect will introduce restrictions to the set of analysed solutions.

Wind farms from 152.5 to 162.5MW in 2.5MW steps and electrolysers from 2.5 to 12.5MW in 2.5MW steps have been evaluated. The electrolyser maximum size has been limited for all the cases to the maximum curtailed power. The maximum curtailed power corresponds to the difference between the installed wind power and the power connection point export limit. Table 26 summarises the evaluated alternatives.

Table 26. Scenario 2 Somela Wind-H$_2$ evaluated alternatives.

Wind farm Power (MW)	Electrolyser Power (MW)
152.5	2.5
155.0	2.5 / 5
157.5	2.5 / 5 / 7.5
160.0	2.5 /5 / 7.5 / 10
162.5	2.5 / 5 / 7.5 / 10 / 12.5

Figure 25 shows the H$_2$ production costs for 2017 MAWPS electrolyser targets for different green tariffs (reported with different shades of blue). As it can be seen the obtained results are quite high, actually the lowest price (13,621€/t) corresponds to the 162.5MW wind farm and a 2.5 electrolyser. Additional studies have been carried out to analyse if better LOCH2 can be obtained when considering the electrolyser data targets for 2023.
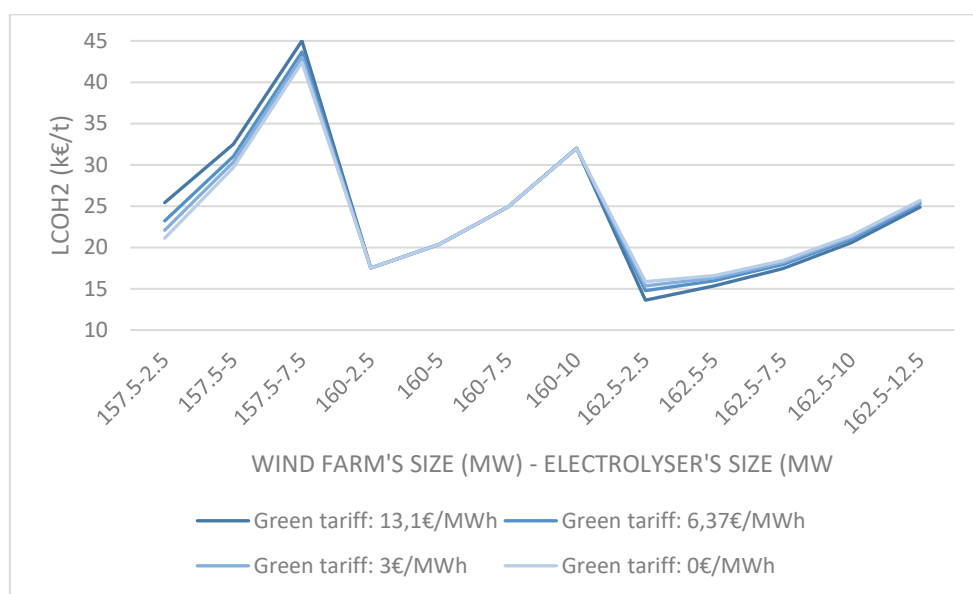
Figure 25. Scenario 2. LCOH2 with 2017 MAWP electrolyser targets.

Figure 26 shows the H$_2$ production costs for 2023 MAWPS electrolyser targets for different green tariffs (reported with different shades of blue). As it can be seen, the LCOH2 significantly decreases for electrolyser characteristics according to MAWP 2023 targets, this is due to the high weight of the electrolyser CAPEX in the cost of H$_2$. For the best case (162.5MW-2.5MW) the LCOH2 is 8,864€/t, which implies a reduction of 35%. Main differences between 2017 and 2023 data are summarised in Table 27.
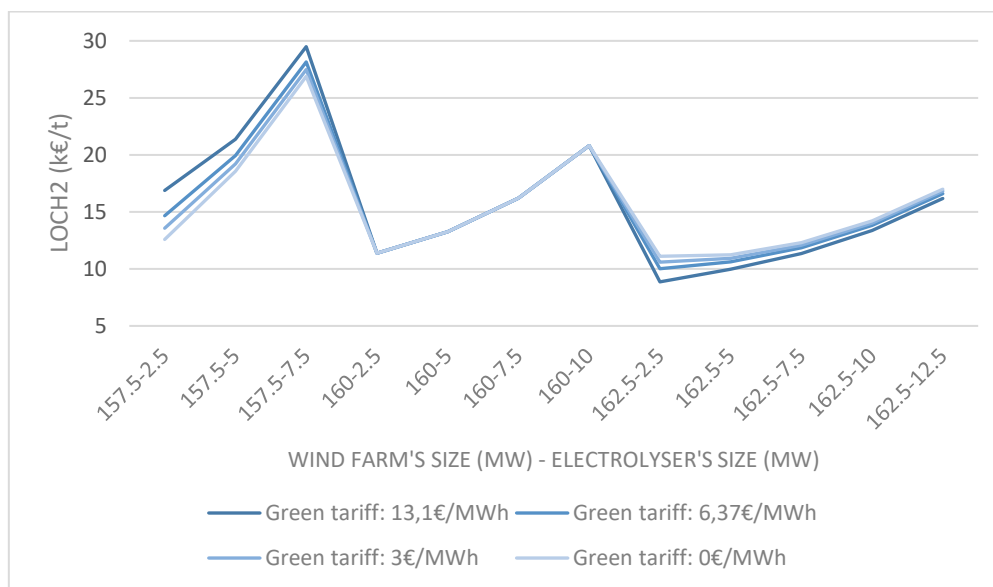
Figure 26. Scenario 2. LCOH2 with 2020 MAWP electrolyser targets.

Table 27. Main electrolyser data difference for 2017 and 2023 MAWP's target values.

2,5MW PEM Electrolyser		
Parameter	2017 Value	2023 Value
Efficiency degradation at rated power and considering 8000 h operations / year	2%/year	1%/year
CAPEX-electrolyser (€/kW)	1,328	538
Overhaul costs* (€/kW)	354	144

The effect of green certificates depends on the size of the wind farm. When the wind farm is small then the LCOH2 decreases with the increase of green certificates, which is the opposite trend as the wind farm increases. This effect on the H$_2$ cost is due to the following reasons:

- The cost of energy does not affect to the LCOH2, because the electrolyser is powered with energy from curtailments, which is a zero-cost energy.
- High energy remuneration improves the NPV of the wind farm and this permits to reduce the cost of the wind farm directly associated to H$_2$ production.

Figure 27 shows the difference in the annual H$_2$ production achieved by the analysed configurations. With respect to this, it is important to highlight that the calculated LCOH2 only makes sense if there is a market for the produced H$_2$.
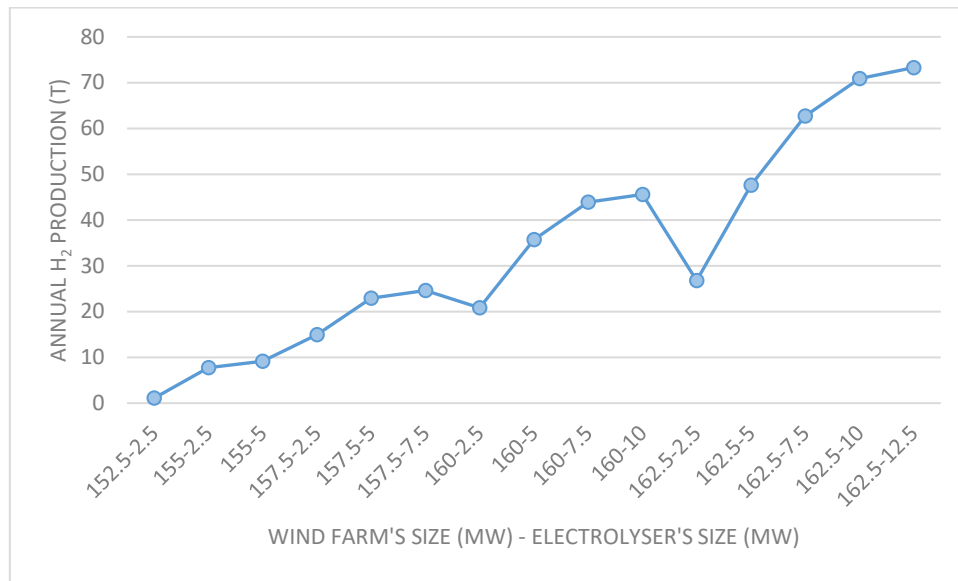
Figure 27. Scenario 2. H$_2$ yearly production.

As it can be seen in Figure 28, the distribution of power cuts is fairly equal, i.e. there is no predominant power cut. However, given the low number of hours with curtailments, less than 8.2%, and the high impact of the electrolyser CAPEX on the LCOH2, the optimal electrolyser size for all the considered wind fam sizes is below the curtailed peak power. As result, the energy losses due to the power connection point congestion are not fully eliminated.

Summarising, the main reasons why prices are so high is the low energy available once the restriction is applied.
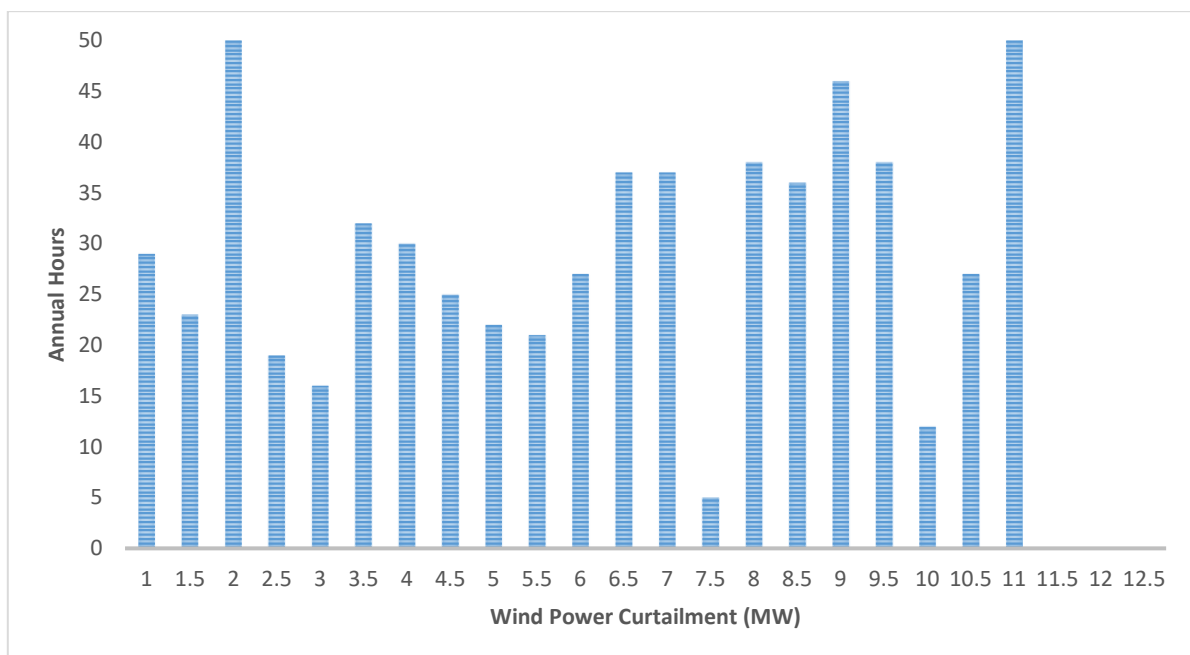
Figure 28. Scenario 2. 162.5 wind farm power curtailments histogram.

Table 28 reports the results for the most relevant configurations for 2017 MAWP electrolyser targets.

Table 28. Smøla wind farm. Scenario 2. Summary of results.

		Base Case 160MW wind farm	162.5MW Wind farm	160-2.5MW Wind-H$_2$ System	162.5-2.5MW Wind-H$_2$ System
Wind farm data					
Installed power (MW)		160	162.5	160	162.5
CAPEX (M€)		144	146.25	144	146.25
OPEX. Annual (M€)		6.4	6.5	6.4	6.5
Annual generated energy (MWh)		382,480	388,456	382,480	388,456
Annual energy injected to the grid (MWh)		380,157	384,744	380,156	384,744
Annual electrolyser consumption (MWh)		--	--	1.111,16	1,432.52
Annual energy curtailed (MWh)		--	--	1.212,45	2,280.4
Electrolyser data					
Installed power (MW)		--	--	2.5	2.5
CAPEX (M€)		--	--	3.320	3.320
OPEX. Annual (M€)		--	--	0.150	0.150
Annual generated H$_2$ (t)		--	--	20.80	26.79
Working hours (h)		--	--	505	635
Raggovidda integrated system data					
Green certificates 13,1€/MWh	Annual income (M€)	21.24	21.49	21.33	21.59
	NPV (M€)	62.58	62.57	57.59	57.58
	H$_2$ production cost (k€/t)	--	--	17.51	13.62
Green certificates 6,37€/MWh	Annual income (M€)	18.68	18.90	18.73	18.95
	NPV (M€)	27.56	27.13	22.58	22.15
	H$_2$ production cost (k€/t)	--	--	17.51	14.77
Green certificates 3€/MWh	Annual income (M€)	17.39	17.61	17.42	18.95
	NPV (M€)	10.03	9.39	5.05	4.40
	H$_2$ production cost (k€/t)	--	--	17.51	15.35
Green certificates 0€/MWh	Annual income (M€)	16.26	16.45	16.26	16.45
	NPV (M€)	-5.57	-6.41	-10.56	-11.39
	H$_2$ production cost (k€/t)	--	--	17.51	15.86

From the obtained results it can be concluded that considering the wind resources in Smøla and the current remuneration scheme, it is not economically feasible to increase the installed wind power over the power connection point export limit. To make this configuration profitable it is fundamental to take advantage of the electricity that cannot be fed to the grid. That is, it is fundamental to produce H_2 by electrolysis, so as to achieve very competitive H_2 production costs in the range of 4-5€/kg, below the costs of operating the electrolyser as an ordinary consumer, as well as to have a large amount of energy available from the export restriction.

4.5.4   Conclusions

Both "Optimal H_2 production" and "Congestion management" have been analysed for the Smøla wind farm, located in Norway. Within these scenarios, several use cases have been analysed, for different sizes of the electrolyser and for different price thresholds in the price arbitrage scenario, and different sizes of electrolyser and wind farm in the congestion management scenario. The LCOH2 has been used as main comparison element of the profitability of all the use cases.

In both analysed scenarios "Optimal H_2 production" and the "Congestion Management", the smallest electrolysers resulted the most profitable. However, while the H_2 production costs for "Optimal H_2 production, in the range of 4 to 5k€/t, are competitive according to current state of the art which are about 6k€/t [7], the costs for "Congestion Management", in the range of 8 to 13k€/t for electrolyser 2023 and 2017 data respectively, are not competitive.

The results have shown that for the case of Smøla the electrolyser utilization factor is very low, spending 93% of the time in standby. As the H_2 production costs are mainly driven by the electrolyser CAPEX, there is a lot of room for decreasing them by increasing the production. In this sense, as seen in the congestion management scenario, the reduction of the costs associated to the electrolyser, which are expected to reduce significantly in the years to come, will also reduce the H_2 costs significantly. Regarding the operation strategies, the combination of strategies for congestion management and for H_2 production at low energy costs could also reduce these costs.

4.6   Moncayuelo Case Study

The objective of this study is to assess the expected H_2 generation of the wind park in Moncayuelo, Spain, which characteristics were introduced in section 3.3. The electrolyser performances are studied by operating it in compliance with Scenario 1 - Optimal Hydrogen Production and with Scenario 3 - Secondary Frequency Regulation. For each scenario, several use cases are presented, mainly related to various electrolyser sizes.

4.6.1   Base Case Scenario: wind farm without electrolyser

The study related to the Base Case Scenario for the Moncayuelo Case Study has been done on the basis of 2017 production and market data for a 20 years period. Table 29 and Table 30 summarise the Base Case Scenario configuration data and results.

---

[7] "*Green hydrogen — produced by electrolysis (splitting water molecules into hydrogen and oxygen) inside machines called electrolysers — today costs roughly $6/kg.*" https://www.rechargenews.com/transition/green-hydrogen-cheaper-than-unabated-fossil-fuel-h2-by-2030-hydrogen-council/2-1-741658

Table 29. Raggovidda wind farm configuration data.

Base Case Scenario: 48MW Moncayuelo wind farm	
Parameter	**Value**
Installed Power	48MW
Annual Generated Energy	145,384MWh
Mean power	16.59MW
Capacity factor	34.57%
CAPEX	43,2.M€
Initial capital costs (40% of CAPEX)	17.3M€
Debt cost (real value)	32.2M€
Total (real value)	49.5M€
OPEX Annual	1.92M€
OPEX total (real value)	47.6M€

Table 30. Base Case Scenario. Moncayuelo wind farm economic performance results.

Base Case Scenario: 48MW Moncayuelo wind farm	
Parameter	**Value**
Annual Incomes	8,423,261€
NPV	43,940,233€
LCOE	32.37€/MWh

The results show that Moncayuelo wind farm has a capacity factor of about 34%, which is around average values for onshore wind farms that are around 34% [19] and higher than Smøla (section 4.5.1).

4.6.2 Optimal Hydrogen Production. Scenario 1

In this scenario the optimal hydrogen production for Moncayuelo wind farm is analysed when a fixed threshold strategy is used. In Table 31 prices thresholds are shown for each of the use cases explained in section 4.3.2.

Table 31. Moncayuelo. wind farm fixed thresholds for optimal H_2 production (Scenario 1).

	Moncayuelo Scenario 1: Optimal H_2 production thresholds	
	Low	**% of values**
UC1	29	3
UC2	41	10
UC3	51	25
UC4	55	35
UC5	84.15 (max. Price)	100% below

Table 32 shows an example of the electrolyser performance in relation with the wind farm generated power and the electricity market price.
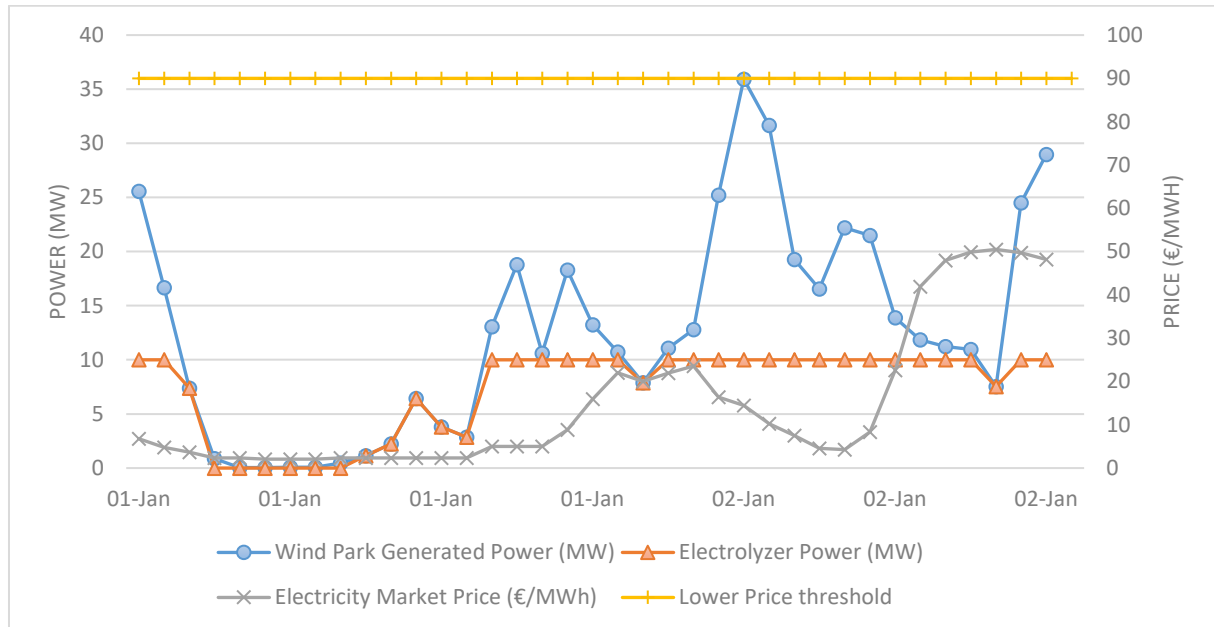
Figure 29. Moncayuelo. Scenario 1, UC1, battery performance example.

As mentioned above, the LCOH2 is used to compare the suitability of the different solutions (use cases 1 to 5). Table 32 shows the results obtained in the simulations for a 2.5MW electrolyser.

Table 32. Moncayuelo. Scenario 1 Results summary for a fix price threshold strategy of 50€/MWh.

	Base Case	UC1	UC2	UC3	UC4	UC5
Wind farm data						
Installed Power (MW)	48	48	48	48	48	48
CAPEX (M€)	43.2	43.2	43.2	43.2	43.2	43.2
OPEX. Annual (M€)	1.92	1.92	1.92	1.92	1.92	1.92
Annual Generated Energy (GWh)	145.4	145.4	145.4	145.4	145.4	145.4
Scenario data						
Low price operation threshold (€/MWh)	--	29	41	51	55	Max Price
Electrolyser data						
Installed Power (MW)	--	2.5	2.5	2.5	2.5	2.5
CAPEX (M€)	--	3.32	3.32	3.32	3.32	3.32
OPEX. Annual (M€)	--	0.15	0.15	0.15	0.15	0.15
Annual Generated H2 (t)	--	8,9	30,3	77,4	105,7	307,1
Working hours (h)	--	209	696	1774	2430	7009
Integrated system data						
Annual injected energy (GWh)	145.4	144.9	143.8	141.2	139.7	128.9

Annual Incomes (k€)	8,423	8,416	8,374	8,256	8,176	7,476
NPV (k€)	43,940	38,861	38,328	36,807	35,662	25,580
LCHO2 (€/t)	--	41,731	13,544	6,731	5,720	4,368

According to the simulation results, the best option is to produce and sell as much hydrogen as possible to get the best NPV values. When the hydrogen is produced at higher market prices, the hydrogen production cost can be considered higher. However, this is not strictly true, since the cost of producing the energy is the same. Actually, as can be seen in UC5, less energy is sold to the market at high prices and, therefore, the energy incomes reduce. This, together with overhaul costs related to the need to the stack replacement, in UC4 and UC5, reduces the NPV of the whole system. Even so, the bigger generated amount of hydrogen and the fact the overhaul cost is smaller than the CAPEX compensates this drawback and the LCOH2 reduces with the increase of working hours of the electrolyser.

Similar simulations have been performed for different electrolyser sizes. Table 33 shows the influence of the nominal power of the electrolyser in UC5 (analogous relationships are observed for the rest of use cases).

Table 33. Moncayuelo. Scenario 1 Results summary for a fix price threshold strategy of 50€/MWh.

	Base Case	UC5 2.5MW ELY	UC5 5MW ELY	UC5 7.5MW ELY	UC5 10MW ELY
Wind farm data					
Installed Power (MW)	48	48	48	48	48
CAPEX (M€)	43.2	43.2	43.2	43.2	43.2
OPEX. Annual (M€)	1.92	1.92	1.92	1.92	1.92
Annual Generated Energy (GWh)	145.4	145.4	145.4	145.4	145.4
Scenario data					
Low price operation threshold (€/MWh)	--	Max Price	Max Price	Max Price	Max Price
Electrolyser data					
Installed Power (MW)	--	*2.5*	*5*	*7.5*	*10*
CAPEX (M€)	--	3.32	6.64	9.96	13.28
OPEX. Annual (M€)	--	0.15	0.3	0.45	0.6
Annual Generated H2 (t)	--	307.1	582.8	836.3	1,070.2
Working hours (h)	--	7,009	6,862	6,747	6,659
Integrated system data					
Annual injected energy (GWh)	145.4	128.9	114.2	100.7	88.3
Annual Incomes (G€)	8,423	7,476	6,627	5,848	5,131
NPV (G€)	43,940	25,580	8,514	-7,628	-22,463
H2 production cost (€/t)	--	4,368	4,442	4,506	4,534

In this case, the investment of the plant provides lower profitability with the increase of the electrolyser size. This is clear because the CAPEX and the OPEX increase, while the incomes for the sale of electricity reduce. However, here the LCOH2 is also lower when the use of the electrolyser, in terms of working hours, is higher.
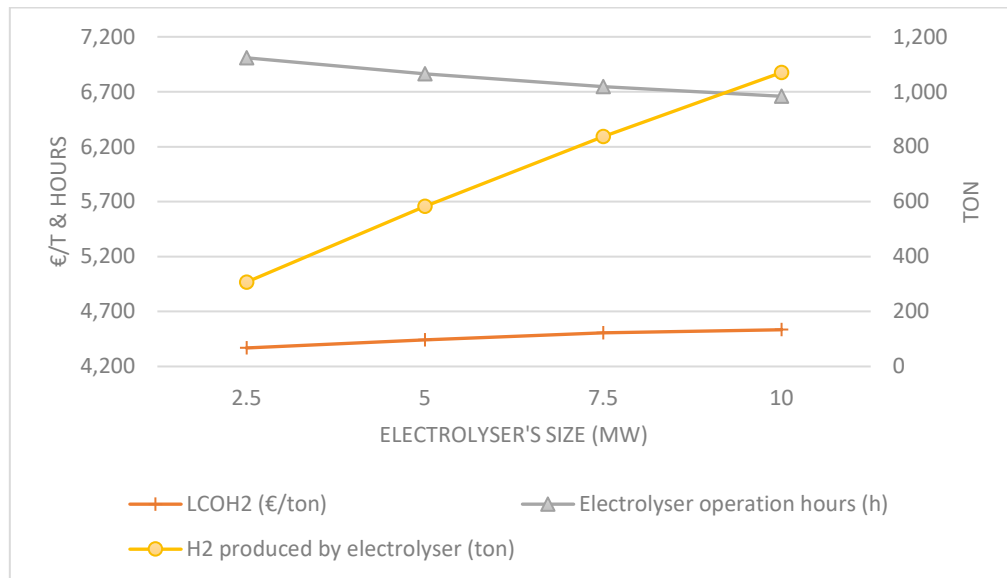
Figure 30. Moncayuelo. Scenario 1, simulation results: LCOH2, working hours, produced H₂.

Figure 31 shows the LCOH2 for all the analysed cases.
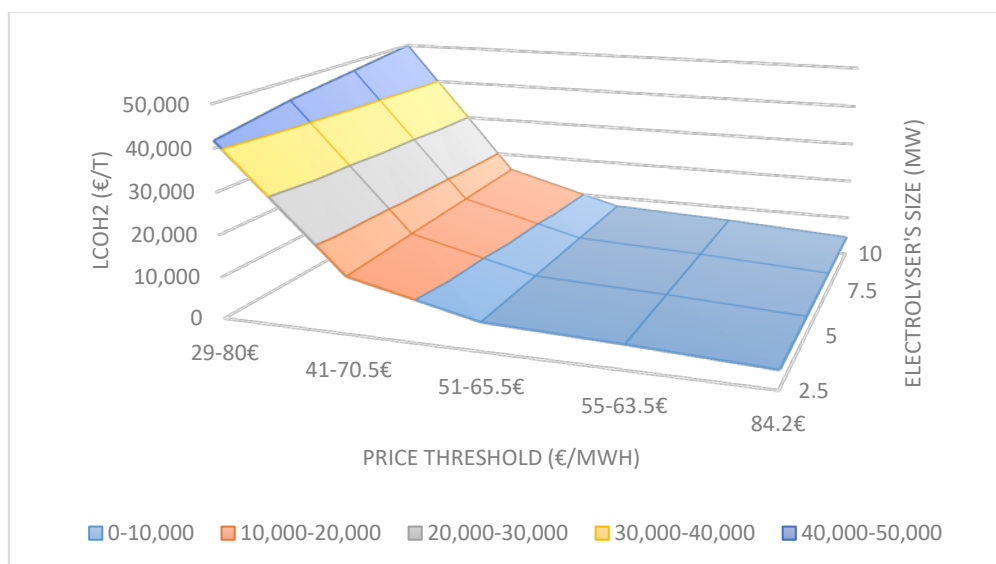
Figure 31. Moncayuelo. Scenario 1, LCOH2 for all use cases and electrolyser sizes.

It has to be mentioned that UC5 is not really an optimal H_2 production case, since the electrolyser operates all available hours independently of the price. Nevertheless, this shows that the profitability depends on the usage.

This scenario is based on the secondary frequency regulation, as defined in the Spanish ancillary market [17]. The electrolyser, together with the wind farm, operates in order to provide this service. The secondary regulation service consists of several processes that are described, in general terms, below:

- *Allocation of the service:* during the generation programme definition process, in the day-ahead wholesale market, secondary frequency regulation reserves are settled. The Transmission System Operator (TSO) requests a regulation band for each area and market period in the following day. Service providers offer their power increase and decrease capabilities together with a price (€/MWh). The TSO allocates the service considering capacity requirements and minimum costs for each of the periods.
- *Activation of the service:* if secondary regulation is effectively needed, a central control system calculates up or down deviations and sends control signals to allocated generators in an area, through an area control centre, which forwards the settings to the involved production or demand units. This is performed automatically by the AGC (Automatic Generation Control) systems.
- Two other processes related to this scenario are the measurement of the response of service providers (identification of fulfilment or deviations in the band and energy request) and the payment for the service.

The simulations for the current study have been performed based on the following considerations:

- The TSO provides data about the secondary regulation service through its ESIOS [18] platform for all market periods (hourly, in this case), that is the assigned band down (MW), the assigned band up (MW), the energy used down (MWh), the energy used up (MW), the band price (€/MWh), the energy price down (€/MWh) and the energy price up (€/MWh). The data of year 2018 have been used as input for the simulations.
- Even if both down and up requests take place within most hourly market periods, the net energy request within each hour has been considered for the simulations. The requested net energy, which is a value for the whole Spanish peninsular system, is calculated as percentage of the requested band for that hour, depending on its sign (negative for down, positive for up). This percentage represents the requested energy to individual units by the AGC.
- The operation rate of the electrolyser, from its minimum to maximum defined power, is offered as secondary regulation capacity band for each hour. This total band is split in two, up and down bands, with the same power relationship between them as that requested for the whole system.
- Since the electrolyser is an electricity consumption device, in order to be able to provide up and down services, a central operation point is selected on day-ahead basis for next day programme: within the day, in response to the AGC signal, consuming less would mean providing energy up, and consuming more than foreseen would provide energy down. See Figure 32 as example of the operation of a battery (some hours presented).
- The wind farm needs to produce a minimum power to proceed to place an offer for the secondary regulation service (10%). If this power is not reached, secondary service is not provided for that hour (see Figure 32. Moncayuelo. Scenario 2, Storage central power (blue dots) and offered band for secondary service (vertical grey lines).).
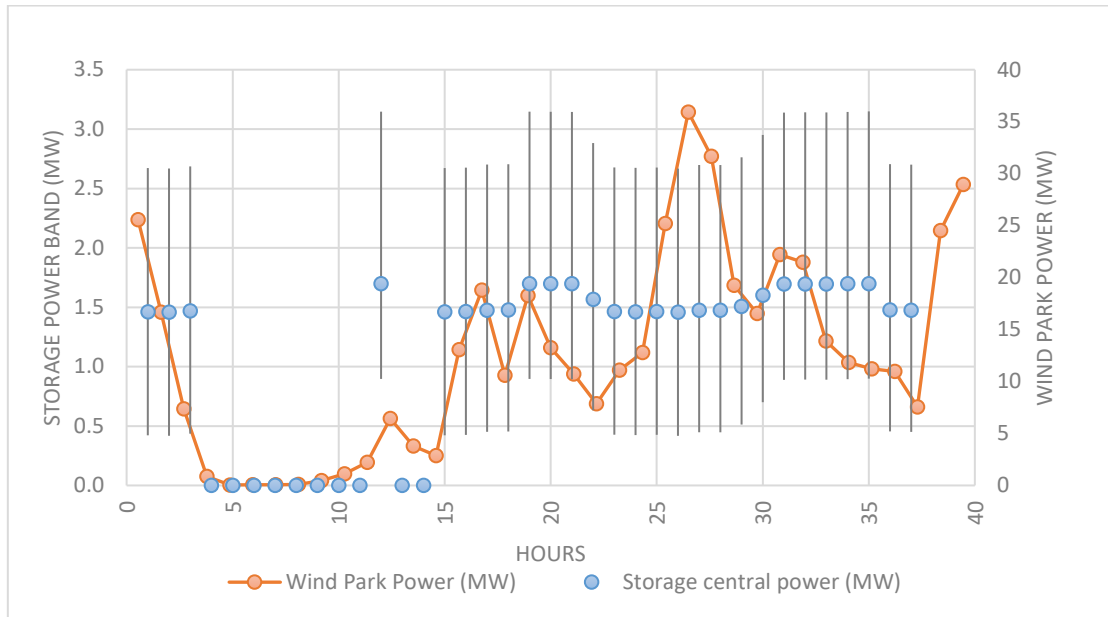
Figure 32. Moncayuelo. Scenario 2, Storage central power (blue dots) and offered band for secondary service (vertical grey lines).

- The energy requested to the storage to provide the secondary regulation service is calculated from the AGC signal, in percentage values. The up/down band available by the storage is calculated as described above (Storage central power (MW)). The final storage power is calculated by subtracting the requested power to the central power calculated before. See an example in Figure 33 (negative power means power reduction request).
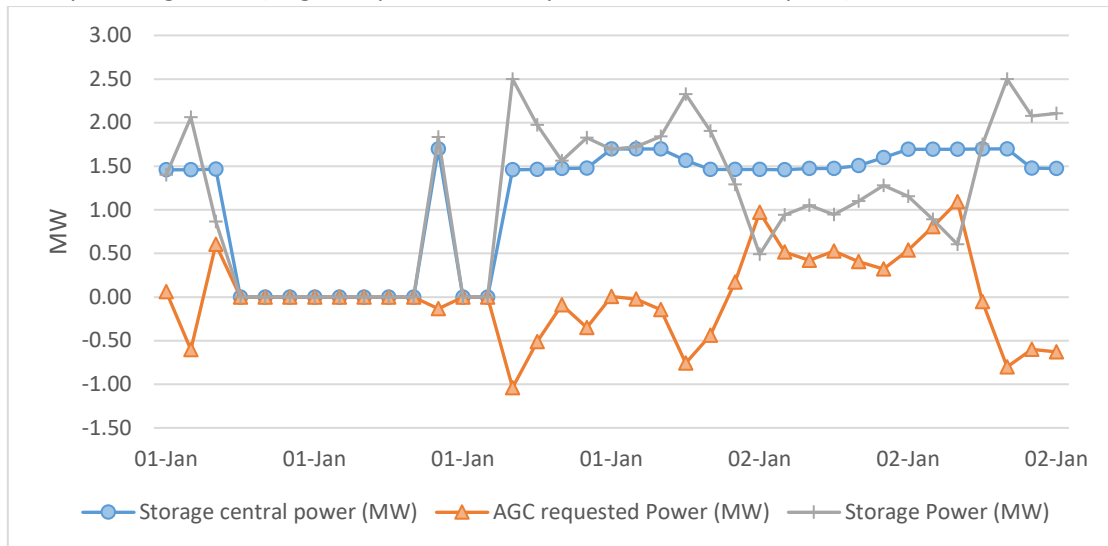
Figure 33. Moncayuelo. Scenario 2, Storage central power, AGC requested power and total Storage operation power.

- Regarding the payment, two concepts are considered: one related to the band (available capacity) and one related to the energy provided, down or up (when requested).
- No penalties are considered: it is supposed that the energy production forecast is perfect.

The performance of the storage has been simulated in accordance to the described service provision. Four electrolyser sizes have been simulated and the LCOH2 value has been calculated for comparison purposes. The results are shown in the Table 34.

Table 34. Moncayuelo. Scenario 2 Results summary for four electrolyser sizes.

	Base Case	2.5MW	5MW	7.5MW	10MW
Wind farm data					
Installed Power (MW)	48	48	48	48	48
CAPEX (M€)	43.2	43.2	43.2	43.2	43.2
OPEX. Annual (M€)	1.92	1.92	1.92	1.92	1.92
Annual Generated Energy (GWh)	145.4	145.4	145.4	145.4	145.4
Electrolyser data					
Installed Power (MW)	--	2.5	5	7.5	10
CAPEX (M€)	--	3.32	6.64	9.96	13.28
OPEX. Annual (M€)	--	0.15	0.3	0.45	0.6
Annual Generated H2 (t)	--	170	337	464	569
Working hours (h)	--	5,703	5,665	5,204	4,799
Integrated system data					
Annual injected energy (GWh)	145.3	136.6	128.0	121.4	116.0
Annual Incomes – energy sale (G€)	8,423.3	7,941.9	7,467.0	7,104.7	6,802.1
Annual Incomes – scenario (G€)	0	145.6	288.9	396.2	486.5
NPV (G€)	43,940	33,824	23,770	14,878	6,869
H2 production cost (€/t)	--	4,357	4,372	4,577	4,759

In this case, from the obtained results it can be concluded that the higher the electrolyser power, the higher the price of hydrogen that would achieve matching the NPV (LCOH2) of the Base Case Scenario is. In turn this implies that the smaller the size of the storage, the better the investment is, which is also reflected in the NPV, as it is shown in Table 34.

Two main reasons cause this result:

1. The electricity required to operate the electrolyser causes an energy sale income loss, which is not compensated by the revenues obtained from the secondary regulation service.
2. The working hours reduce with the increase of the electrolyser size. This occurs because no secondary offer is placed if the wind park does not generate a power above the electrolyser maximum power and, therefore, the higher the electrolyser size, the lower the amount of available hours to provide the secondary reserve service. Results would improve without no such condition.
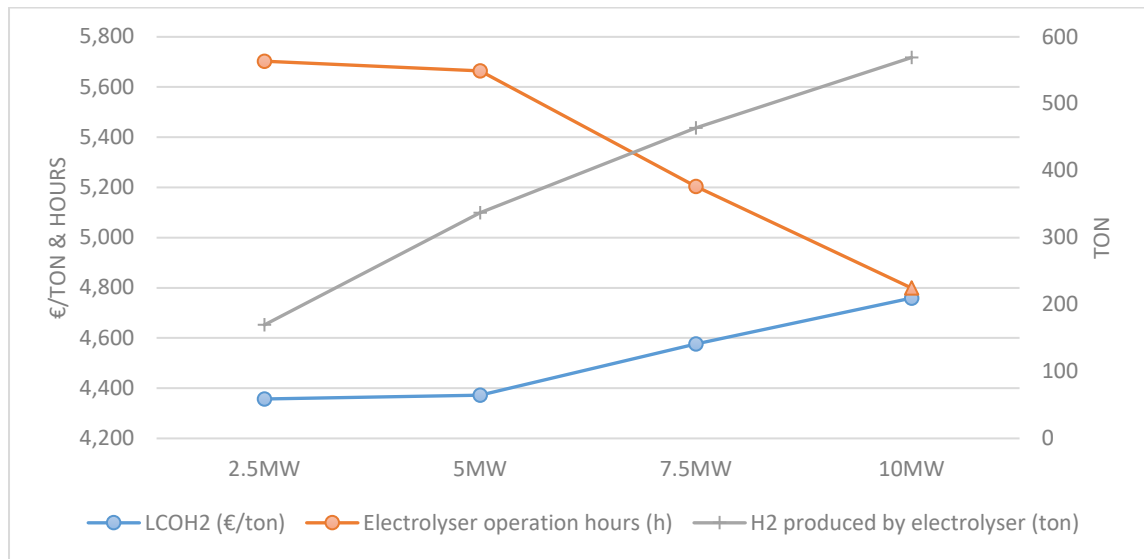
Figure 34. Moncayuelo. Scenario 3, simulation results: LCOH2, working hours, produced H₂.

4.6.4 Conclusions

Both "Optimal H₂ production" and "Secondary frequency regulation" have been considered to simulate the performance of an electrolyser in relation with the Moncayuelo wind farm, located in Spain. Within these scenarios, several use cases have been analysed, for different sizes of the electrolyser and, in the "Optimal H₂ production" scenario, for different price thresholds. The LCOH2 has been used as main parameter for the comparison of the profitability in all the use cases.

In both "Optimal H₂ production" and "Secondary frequency regulation" scenario simulations, the smallest electrolysers resulted the most profitable. Linked to this outcome, the following principle stands: the higher the amount of working hours of the electrolyser, the lower the LCOH2 and, therefore, the better the results are.

Comparing both scenarios, secondary reserve service provides better results (4,357€/t) than the best optimal H₂ production use case (4,368€/t for UC5), with a minimal difference. Henceforth, similar hydrogen sale prices are obtained with significantly less hours of operation. Two remarks need to be made on this statement:

1. UC5 is not really an optimal H₂ production case, but a reference case, where the electrolyser is operated for the longest possible period, with those scenario conditions (this is in line with the previous comment on the working hours influence on results).
2. In the secondary regulation service scenario, other operation principles would have provided better results. For example, allowing the operation at partial load of the electrolyser (by eliminating the restriction that the wind park should produce more power than the nominal of the storage).

The obtained H$_2$ production costs for both scenarios, which are about 4.4k€/t, are competitive according to current state of the art which are about 6k€/t [8].

In Figure 35 both scenarios are compared. Particularly the LOCH2 and the working hours results for scenario 1, UC5, and scenario 2 are reported.
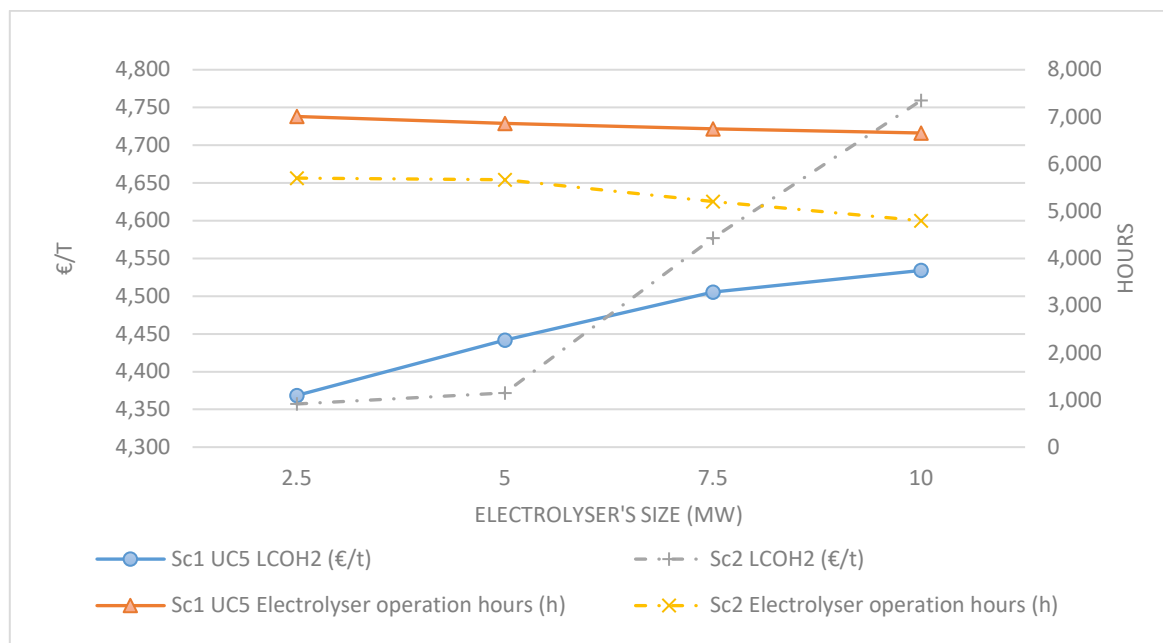
Figure 35. Moncayuelo. Scenario 1 UC 5 and Scenario 2, simulation results: LCOH2, working hours.

Even if the improvement of the electrolyser cost and performance in the years to come has not been considered, it is clear that obtained results would improve with time.

A last aspect to be highlighted is that these results provide comparison means for different scenarios and use cases, but they contain several simplifications. Especially, the fact that wind energy generation forecasts are 100% accurate is far from reality. Therefore, the results must be considered as illustrative.

---

[8] *"Green hydrogen — produced by electrolysis (splitting water molecules into hydrogen and oxygen) inside machines called electrolysers — today costs roughly $6/kg."* https://www.rechargenews.com/transition/green-hydrogen-cheaper-than-unabated-fossil-fuel-h2-by-2030-hydrogen-council/2-1-741658

5 Socio-economic analysis of wind-hydrogen systems (SINTEF)

5.1 Methodology

5.1.1 The effect on local and national economies and potential for job creation

For the socio-economic analyses of new hydrogen plants and potential effects of the job creation from the plants, we use an Input-Output (I-O) model. Our estimation of the I-O multipliers is based on the Leontief [20] model. We refer to, e.g., Miller and Blair [21] for detailed explanations. The I-O model relates the gross output X of the sectors in an economy to the technical coefficient (input) matrix A and the final demands y for the output from each sector:

$$X = AX + y,$$

where $A := a_{i,j} = z_{i,j}/X_j$ is a matrix of input coefficients indicating how many units of inputs from sector i to j are required to produce one additional unit of output for sector X_j, thus reflecting the economy's production structure and $z_{i,j}$ is the intermediate demand of inputs from supplying sector i to receiving sector j. The A matrix shows the proportional relationship between the sectors' inputs and outputs, reflecting the economy's production structure. A trivial matrix operation transforms Equation 7 to

$$X = (I - A)^{-1}y = Ly,$$

where I is the identity matrix of suitable dimensions. Equation 8 expresses the total output solely as a function of the final demands and the sectors' production functions, also known as Leontief inverse (or multiplier) matrix L, which can be derived from statistical data. These backward linkages in the form of multipliers help to determine how a change in the final demand (Δy) affects total output in the economy. To quantify the total effects for local and national economies of new hydrogen plants, we adjust the initial final demand vector y to a new demand vector where the final demand from the hydrogen plant is included. The difference between the two situations where we use y and y^* will reflect the total effects on outputs, that is,

$$\Delta X = (I - A)^{-1}y - (I - A)^{-1}y^*.$$

From ΔX we will gain insights of the total economic effects on output for the investments and operating demand for the hydrogen plant. We assume a constant relationship between value added and output and employment and output, thus from Equation 9 we can calculate the effects on jobs proportionally to change in output. Depending on the geographical scope of the data, the above calculations can be performed on national or local level. To calculate the effects from such I-O model, we use an operating I-O model for Norwegian regions called PANDA (https://www.pandaanalyse.no/pandamodellen/) for the Norwegian cases Smøla and Berlevåg. Based on the results from these cases, we try to generalise further to the Moncayuelo case.

5.1.2 Data required and availability

Data required is a national and local/regional I-O dataset. We also need data on investment and operating costs for each hydrogen plant grouped by industry and geographical impact field.

5.1.3 Applicable policies and regulations

A qualitative assessment of relevant regulations, codes and standards has been carried out, to supplement the model-based analyses on potential and possible multiplier effects. The assessment

draws on previous findings from the HyLAW project, which assessed around 70 legal-administrative procedures for 18 European countries in a structured manner [22]. Apparent and potential structural and operational barriers, and/or regulatory gaps were identified, and their severity was assessed nominally, in consultation with key stakeholders in each country.

Considering the scope of this deliverable, the discussion of regulations, codes and standards is placed within the present policy context surrounding hydrogen as energy carrier. Here, we draw upon preliminary findings from a project called Norwegian Energy Roadmap 2050, which includes a case-study on the potential for hydrogen production in Norway and discussion of the European context [23]. The pilot and possibilities explored for Raggovidda was included as one out of six initiatives, where key stakeholders were interviewed, and publicly available information was assessed in detail.

For HAEOLUS, a document study on legal-administrative aspects of hydrogen and power-to-X has been added. This was limited to documents available through Web of Science and Google, from 2016-2019. We have also consulted key stakeholders in relation to the Norwegian case studies, including VarangerKraft Hydrogen, VarangerKraft Nett, Norsk Vindenergisenter at Smøla, the Norwegian Water Resources and Energy Directorate, Statnett, and the Directorate for Civil Protection (DSB), to be able to include the latest experiences and perceptions of the case owners and ensure that we are updated on the latest regulatory changes. For Spain, attempts were made to contact Acciona and the Aragon Hydrogen Foundation. However, the assessment is mainly based on HyLAW and public documents available in English, with inputs from the Spanish project partners.

5.2   Summary of local job effects for the three cases

The assessment of local job effects rely on the data input on operating and investments costs of the hydrogen plant. For the Raggovidda case such data has been provided by Syd-Varanger Kraft. For the Smøla and Moncayuelo case, we rely on the example data from Syd-Varanger Kraft. The local job effects upstream spillover effect in the value chain have be quantified but not the downstream effects. This is due to missing data. However, we discuss different opportunities of local downstream use for the three cases, which further may turn into new local jobs. Table 35 summarise the employment effects from the three cases and with employment multipliers related to MEuro of electrolyser production value

Table 35 Summary of job effects for the three cases

Local job effects	Raggovidda	Smøla[9]	Moncayuelo
Investments period (short run)	9	9	9
Direct + upstream (permanent effects)	4	4	4
Downstream	+	100	+
Additional municipal tax income	+	+	+
Investments multiplier of full-time jobs per MEuro of electrolyser production value	6,7	6,7	6,7
Operating multiplier of fulltime jobs per MEuro of electrolyser production value	3,0	77,1	3,0

---

[9] Assuming that the hydrogen will be used downstream locally to establish a new hatchery for salmon.

Comparing the results in Table 35 to other analyses of socio-economic effects of the hydrogen value chain, we see e.g., estimates of national employment multipliers on 5.5 full time employees per MEuro of electrolyser.[10] Our results are lower, about 3, but we estimate results on local level (for a municipality/region) and did not have detailed data on the local downstream use of hydrogen. One idea for local use of hydrogen in the Smøla case, is to use hydrogen as energy-input in a new hatchery for salmon. If this is realised a large amount of new jobs will be established downstream because of the hydrogen plant. Such a downstream scenario will push the multiplier to a high level for Smøla, and this shows how sensitive the local job multipliers are for the downstream use of hydrogen. Additional municipal tax income originate from the hydrogen plan could also transmit into local public jobs through increased local public tax income. These numbers are difficult to relate directly to the output-size of the hydrogen plant, but could for some cases (e.g., Berlevåg municipality) become significant.

5.3   Raggovidda Wind Farm Case Study – Berlevåg municipality

Berlevåg is located in the north of Norway and close to the coastline. It is a small municipality with a population of 1000 persons and 430 employees. Table 36 shows how the employees are distributed by industries. Traditionally, fisheries and the attached processing industries were the most important employers in the municipality. In addition, we see that public administration and other services plays an important role in the local community.

Table 36. Number of employees by industry Berlevåg.

Municipality Berlevåg	Employees 2018	Employment Shares
Agriculture. forestry and fishing	72	16.7%
Crude oil and natural gas. extraction and pipe transport	0	0.0%
Industry and mining	89	20.7%
Power and water supply	3	0.7%
Construction	18	4.2%
Wholesale, hotel and restaurant activities	48	11.2%
Transport and communication	37	8.6%
Finance and business services	15	3.5%
Public administration and other services	148	34.4%
Unknown	0	0.0%
Total	430	

A wind-hydrogen system demands both investments in windmill plant and a hydrogen factory. In all cases we analyse, the windmill plants were already established for several years ago, while the hydrogen factories are only ones built now during this project or planned built soon. Since the wind plants are built for many years ago, we do not have any investments data or operating data from these plants. However, previous reports on windmill plants investments in Norway such as Riise et. al [24] and Riise et. al [25] provide an idea of expected local and national value added effects from new wind

---

[10] Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies FCH contract 192, Evidence Report.

mills. The value creation share from these wind farm investments was between one fourth to one fifth. Although wind turbines are produced abroad, a considerable part of value creation could be attached to Norwegian value added.

We will use the numbers from the Smøla case in this study as a reference. Smøla I and Smøla II refer to the first and second step of the building of the wind park in Smøla. The total investments in the wind park in Smøla I was 316 mill (million) NOK in 2002 and for Smøla II 860 mill NOK in 2005. Only 21 percent of the investments were demanded by Norwegian suppliers, while only 9 percent were from local companies. In 2014 they had operating cost on 34 mill NOK. 93 percent of these costs were connected to Norwegian suppliers, while 81 percent was demanded from regional/local suppliers. Total effect from Smøla wind farm is today 150MW and with an estimated yearly production of 356 GWh. Hence if the inflate adjust these numbers to 2018 and make the value added relative to the estimated yearly production of GWh, for Smøla we achieve multipliers as reported in Table 37.

Table 37. Value added multipliers related to size of GWh windmill production based on Smøla data.

	Investments	Operating
National	1.0	0.1
Local	0.4	0.09

5.3.1 Upstream spill over industrial effects

In Table 38 we show the estimated hydrogen output, investments and operating suppliers by industry and geographical impact field. The estimated output from the hydrogen plant is 390 t/y with an estimated yearly energy use of 22 GWh. Step one of the wind-hydrogen system is already established in Raggovidda, therefore the national and local effects from the first phase is not really related to the building of the hydrogen factory, but we are interested to see these economic effects in relation to the energy use of the hydrogen plant. If we use the data from Smøla, from Table 38 we see that, e.g., we could have expected 22 mill. NOK in national value added from investments and 8.8 mill. NOK in local effects.

Table 38. Investmens and operating costs for the Hydrogen Plant in Berlevåg/Raggovidda.

Raggovidda Hydrogen Plant (measured in NOK, 2018)		
Investments phase		**Supplier Industry**
Buildings	11,905,000	Construction (Local)
Fiber	288,000	Electricity. gas. steam and air conditioning supply (Local)
Transformer	800,000	Manufacture of computer. electronic and optical products and electrical equipment (Local)
Consultants	745,000	Repair and installation of machinery and equipment (Local)
Electrolyser	15,000,000	Manufacture of computer. electronic and optical products and electrical equipment (Local/National/Foreign)
Operating phase		**Supplier Industry**

Raggovidda Hydrogen Plant (measured in NOK, 2018)		
Power (assumption 37.6€/MWh)	9,150,000	Electricity. gas. steam and air conditioning supply (Local)
Maintenance	480,000	Repair and installation of machinery and equipment (Local)
Output (assumption 390 tonnes pr. year, estimated energy use 22 GWh)	13,500,000	

We implement the data in Table 38 into the I-O model PANDA in order to see the employment effects of the hydrogen plant. In the investment phase we expect local effects for the municipality Berlevåg of about 9 employees. This is a high scenario estimate where we assume that the electrolyser is supplied from a local company. This effect represents an effect of 2 percent of the total amount of the employees in Berlevåg. In the operating phase the local effects for the municipality Berlevåg is estimated to about 4 employees. Figure 36 shows forecasted development with (yellow) and without (blue) the hydrogen plant in Berlevåg.
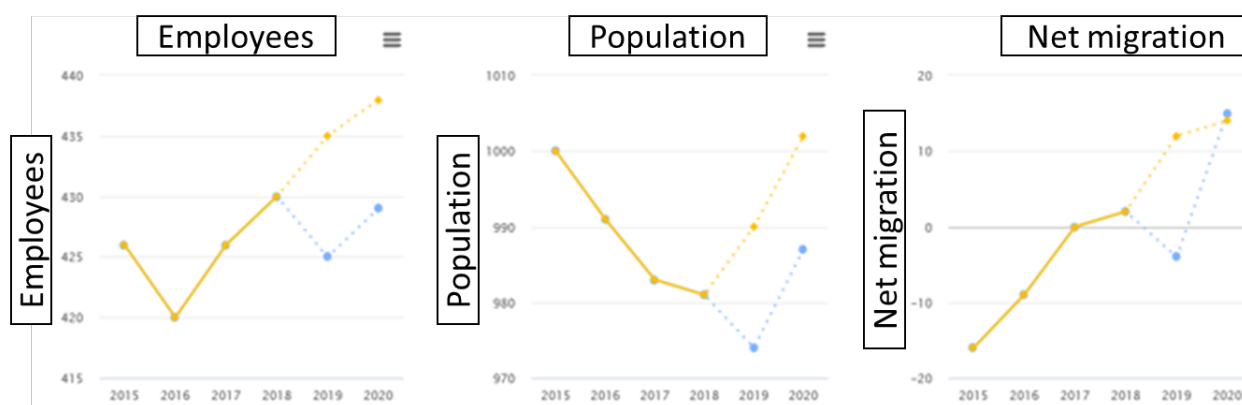
Figure 36. Forecast of future employment in Berlevåg with and without the hydrogen plant.

5.3.2   Downstream spillover industrial effects and other local effects

The I-O model we use to estimate wider economic impacts of a hydrogen plant does not include the economic potential connected to forward economic effects. A new hydrogen plant could be exploited to establish new industrial activity. These effects are hard to measure within a model, thus we have to discuss these potential effects outside a modelling framework. The local administrators and local industry have discussed different scenarios of future industrial use of the hydrogen in Berlevåg, such as:

- Greening the aquaculture industry
- Export the hydrogen to the island Svalbard
- New local industrial use – an industrial cluster in Berlevåg
- Hydrogen energy inputs for Sydvaranger Gruve

The aquaculture industry is not present in the municipality Berlevåg today. However, this an important industry in Norway and in surrounding areas to the municipality Berlevåg. A green energy input option could be important for growth of this industry in the municipality.

Another option is to export all the hydrogen to Svalbard, then there will be only minor local effects from the hydrogen plant. Locally, they must build infrastructure for shipping the hydrogen on boats or alternatively underwater cable infrastructure. These effects will not affect local economy to a large extend.

An alternative use of the hydrogen is to use it locally as energy inputs in an industrial cluster. It is not easy to predict how many additional local workplaces one could expect based on this energy input.

Greening the global economy increases the demand for metals. One example is electric cars, which need much more metals in their production process than traditional fossil cars. The excess demand for metals is good news for the mining industry. This industry has struggled for many years in Norway, but now, due to the climate action focus, the future looks more promising. As the mining industry also is energy intensive, this industry will have to use carbon neutral energy inputs in the future, and one solution is thus to use hydrogen as input. This combination, hydrogen and mining, could have a large economic potential for the local economy in north of Norway in the future.

Berlevåg kommune owns 6.5% of Varanger Kraft AS. In 2018, the surplus in Varanger Kraft was 49.5 mill NOK. The shareholders' meeting decided to pay 35 mill NOK of their surplus to the owners. Hence the municipality in Berlevåg will receive about 2 mill NOK in additional income from the power plant in 2019. Moreover, we expect that in an integrated wind-hydrogen system less energy will get lost from the windmill production, and the profitability of wind powerplant will increase. Berlevåg kommune and the other municipality owners will also benefit from this effect, because of more surplus transfers (owners Varanger Kraft: Sør-Varanger (31.25%), Vadsø (21.87%), Deatnu-Tana (12.5%), Vardø (12.5%), Båtsfjord (9.37%), Berlevåg (6.25%) andUnjárgga-Nesseby (6.25%)).

Whether the municipality has established a real estate tax differs in Norway. Berlevåg kommune waited for a long time before they established this tax. Today, it's an important part of the total tax income of the municipality. In 2016 they expected about 4.2 mill NOK in tax real estate tax income from the power plant.

5.3.3 Legal-administrative drivers and barriers

In Norway, hydrogen is largely regulated as an industrial chemical, together with other inflammable, reactive and pressurized substances. Hereunder, it is classified in hazard category 2, with specific zoning, risk assessment and explosion prevention requirements. The national regulations for production and handling of dangerous goods transpose the *ATEX* and *SEVESO Directives*, which for a large part define the risk and safety requirements [26], [27]. Thus, according to the Directorate for Civil Protection, it is a misunderstanding when some actors claim to be "waiting" for hydrogen as energy carrier to be regulated: it is already regulated, but for some applications specific guidelines and standards are yet to be developed.

As noted above, certain areas of potential use of hydrogen from Raggovidda have been discussed by the local administrators and industry. These can be summed up to a potential value chain consisting of production, storage, distribution, transport, and conversion and use (for decarbonization of transport, industry, and possibly shipment and application for heating/stationary power at Svalbard), as depicted in Figure 15.
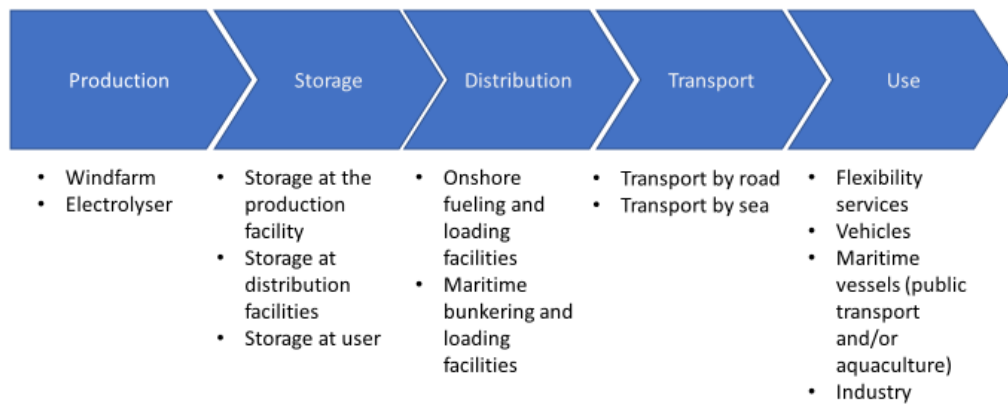
Figure 37. Potential hydrogen value chain, Raggovidda.

In the following, regulations, codes and standards for the respective chain activities are discussed.

5.3.3.1 Production

The establishment of an electrolyser plant requires permission from the municipality. The "umbrella" legislation is the *Planning and Building Act* and the *Pollution Prevention Act*, but it is the *Fire and Explosion Prevention Act* and *Regulation on handling of inflammable, reactive and pressurized substances and equipment and facilities used in the handling of such substances* that requires most comprehensive assessment and documentation [28]. The municipality works as a one-stop shop, and the application process has 3 steps: 1) an initial general permit, 2) a permit to start construction, and 3) operation permit. In some cases, adjustment of the municipal land use plan will be needed, but in the case of Raggovidda the municipality itself proposed a suitable site for the pilot plant (Figure 15).

Figure 38. Pilot plant site at Berlevåg (photo: Federico Zenith).

Obtaining a permit does usually not take longer than for other industrial facilities, less than one year (the total maximum response time for the three steps is 42 weeks). All aspects, environmental, risk, safety, etc. are considered in one, integrated process, and the municipality will consult the relevant agencies. Among these, the local fire and rescue agency is consulted in most cases. The process is relatively time-consuming and expensive, due to comprehensive risk assessments which in most cases

are left to specialized consultants. The cost of the required risk assessment for a smaller facility, like the pilot plant at Raggovidda, is in the range of 250,000NOK, or 25,000€.

If the electrolyser is put up in the immediate vicinity of a wind farm, the explosion prevention document required under the *ATEX directive* will have to address both chemical and el-safety aspects, depending on the hazard zones defined in the given case. Some of the specialized electrical equipment at the windfarm may need explosion-proofing if it falls within the hazard zones. The national *El-safety Act* and *Regulation of electrical low-voltage plants* and the *Regulation of equipment and safety systems for use in explosive atmospheres* are the relevant legislative documents [29], [30] and [31]. The key norm is NEK 420, for electrical plants in explosive hazard zones. This corresponds with the relevant IEC and CENELEC norms, such as EN/IEC 60079 on classification of areas, equipment protection and testing requirements, which are function-based, not fixed. The additional requirements may involve some additional costs, but the closest hazard zones will not be extensive – rather limited to a few meters.

If the plans involve storage capacity of 5 tonnes or more, special consent from the Directorate for Civil Protection is required, under the regulation on *Control of Major Accident Hazards Involving Dangerous Substances* [32]. There is a *Guideline for obtaining Special Consent*, which defines the information and documentation requirements, as well as the application and case treatment procedure [33]. This procedure will be needed in the case of full-scale hydrogen production at Raggovidda. Up to now, the procedure has not been carried out specifically for a hydrogen production facility. However, it is based on the *SEVESO Directive* and brings in certain additional obligations, e.g. notification of all concerned establishments, deploying a major accident prevention policy, producing safety reports and internal emergency plans. A full Environment Impact Assessment (EIA) may also be required. In the case of Raggovidda this has already been done for the wind farm, where the Norwegian Environment Agency found little conflict with other environmental concerns [34]. Once established, hydrogen production from electrolysis benefits from an exemption from the state electricity fee, which applies to all power-intensive industry. Enterprise development based on renewable energy is also one out of four strategic focus areas in the national *White paper on energy, of 2016*, and tends to be encouraged by local and regional authorities [35]. Innovative projects including electrolysis and hydrogen deployment may receive grant support from national and local authorities. However, electrolysis itself is considered as a mature technology and therefore not eligible for regular grant support from the state funding agency Enova.

The legal-administrative procedure for connecting an electrolyser to the e-grid is the same as for other connecting prosumer facilities. Under the current regulation Statnett, as TSO, 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. Until 2019 the DSO could decide independently the connection charge to cover the costs of connecting new customers or reinforcing the network for existing customers. Since 1st November 2019, a new *Regulation on grid regulation and electricity market (NEM)*, implementing *EUs Third Energy Package*, states that the DSOs must submit their conditions for approval of production facilities to the recently established independent energy regulator (RME), for individual decisions [36]. Any entity engaged in physical trading, generation and/or distribution of electric energy is required to hold a trading license (previously from the Directorate for Water Resources and Energy (NVE) - now from RME). For all new projects (wind-, gas- and hydro-power plants, power lines, transformers) a license to build and operate must be granted. Economy, organization, public and private interests as

well as environmental issues are to be considered. RME also has the authority to decide on conditions and methods of trade in energy markets.

NVE regulates the DSOs and Statnett using an incentive-based revenue cap model. DSOs are responsible for determining tariffs within their income cap according to the regulation of the tariff structure and required to offer non-discriminatory tariffs and conditions. Any differentiation must be based on objective and verifiable criteria, giving price signals about effective utilization and development of the network. Consumers 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 and consist of an energy component and a fixed component. The fixed component for 2018 was 0.0013€/kWh. Prosumers feeding in less than 100kW are not charged the fixed component for production. The *NEM regulation* opens for connections with flexible production agreements to reduce the need for grid expansion, where both parties agree to this. This may lead to inclusion of more production activities, and according to the Ministry for Petroleum and Energy it will reduce the need for dispensations and related bureaucracy [37].

5.3.3.2   Storage
The regulations, responsible authorities and approval process for storage of hydrogen are the same as for production (see above). In addition, there is a special *Guideline for storage of dangerous substances*, which defines the information and documentation requirements, and again outlines the procedure for obtaining special consent [38]. The latter would be needed in the case of full-scale hydrogen production at Raggovidda, and if the potential export of hydrogen to Svalbard is realized – then a storage of 5 tonnes or more will probably be necessary. The guideline further refers to the national *Regulation of Pressure Equipment*, which implements the *EU Pressure Equipment Directive (PED) 2014/68/EC* [39]. Due to the volume of hydrogen, a storage unit will typically present a larger risk than the electrolyser and be subject to a higher level of safety compliance analysis. The most important hydrogen storage methods are based on either compression or cooling or a combination of the two (hybrid storage). The guideline for storage of dangerous substances defines general requirements as regards zoning, safety distances, preventive measures etc., and includes a list of general standards for dangerous substances and for LNG that will apply as relevant, but none specifically for hydrogen. The *NFPA 2 Hydrogen Technologies Code* is often referred to by Norwegian stakeholders, but the need for function-based requirements is emphasized so far [40].

5.3.3.3   Distribution
Except when it is fed into the e-grid, deployment of hydrogen from Raggovidda will require distribution and transport, either by road or by sea. Supplying hydrogen to an emerging industry cluster in Berlevåg or to Syd-Varanger Gruve would require truck transportation. In Norway, the Directorate for Civil Protection (DSB) is responsible for the national *Regulation of land transport of dangerous goods,* which implements the *ADR European Agreement* concerning the international carriage of dangerous goods by road and the *RID European Agreement*, on international carriage of dangerous goods by railway [41]. Transport on land is further regulated by the *Regulation on transportable pressure equipment*, which implements the *Transportable Pressure Equipment Directive (TPED) (Directive 2010/35/EU)* [42]. The regulation applies to the design, manufacture, and conformity assessment of transportable cylinders, tubes, cryogenic vessels and tanks for transporting gases such as hydrogen. There is some variation across countries in how ADR is operationalized, but in Norway there are no specific

requirements for transportation of hydrogen, in terms of roads, specific routes, or vehicles. The approval processes are the same as for other class 2 gases.

Supplying hydrogen for future power production at Svalbard would require transportation of liquefied hydrogen by boat. 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)* [43], [44]. 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. 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.

A set of *Interim recommendations for carriage of liquefied hydrogen in bulk* (MSC.420(97) has been adopted [45], but so far, the IGC Code lacks specific requirements for hydrogen. Whereas storage of fuel natural gas is allowed on-board passenger ships carrying more than 25 passengers, it is anticipated that initial restrictions on 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* [46].

5.3.3.4   Loading and bunkering installations

The legislative framework for loading facilities is the same as for production and storage of hydrogen (see above). In addition, a national *Guideline for tapping of dangerous substances* will apply. This guideline specifies general competence requirements as well as competence requirements in risk assessment, according to ISO/IEC 17020 [47]. Regular monitoring and updating of risk management plans as per a given standard (NS 5814) are also included. Principally, there are no additional requirements for hydrogen, as compared to for example LNG, but the higher pressure has implications when it comes to safety distances and other precautionary measures. For loading of onshore vehicles, the guideline specifies that the design of refuelling / loading facilities should be according to standard *ISO/TS 20100 Gaseous hydrogen - Fuelling stations*, which includes definition of safety distances.

Specific regulations or standards for maritime hydrogen bunkering facilities have not yet been developed. However, the *Government's Action Plan for Green Shipping* (2019) states that Norway will take a special responsibility in this area [48]. It is anticipated that specific guidelines and standards, based on co-development in ongoing pilot projects, will be provided in the not-too-distant future. The Directorate for Civil Protection has decided that special consent will be required for all maritime hydrogen bunkering infrastructure, regardless of volume and number passengers. When it comes to stationary facilities, this implies that the risk assessment shall include quantitative analysis showing risk contours [49]. For bunkering from trucks, quantitative assessment is not required, beyond the calculations needed to determine the inner hazard zone. For the overall assessment and definition of safety zones, the guideline refers to standard *NS-EN ISO 20519*, for bunkering of LNG ships. The overarching regulatory framework is already established, in the *Regulation on handling of*

inflammable, reactive and pressurized substances and equipment and facilities used in the handling of such substances [28], and the *Guideline for tapping of dangerous substances* [47], which explicitly mentions hydrogen and onshore as well as floating bunkering stations for LNG.

5.3.3.5 Use: Road transport

According to the Norwegian Institute for Transport Economics (2019), the traffic work (ton-kms) on road in Northern Norway and the whole of the country will increase towards 2050 [50]. According to the *Climate Act of 2017* Norway shall cut its climate gas emissions from the transport sector 40% by 2030, and the government recently confirmed a higher ambition; to reduce the climate gas emissions from transport 50% by 2030 [51]. By 2025, all new cars sold shall be zero emission vehicles. The national *Action plan for infrastructure for alternative fuels in transport* has a strong focus on battery electric vehicles (BEVs), but sees a considerable potential for Fuel Cell Electric Vehicles (FCEVs) in heavy duty transport and fleets, especially in areas where charging infrastructure is scarce and costly to develop [52].

The regulations for type approval and permits for FCEVs are harmonised with common EU legislation (notably *Directive 2007/46/EC* and *Regulation 79/2009*) [53]. The requirements and periodic testing /inspection procedures are the same as for other cars. Both BEVs and FCEVs are exempted from VAT, which is 25% for other cars. FCEVs are also exempted from the non-recurrent registration fee, which is a sizeable incentive. Likewise, both hydrogen and battery-electric cars, as well as heavy-duty vehicles, are exempted from the system of traffic insurance fees payable to the state, since 01.01.2018. By a government resolution of 2017, BEVs may be charged up to 50% for parking, in road toll and on local ferries, but FCEVs 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. The *Public Procurement Act* and *Regulation on Public Procurement* encourages use of environmental criteria [54]. Several counties and municipalities have found support for initiatives to introduce FCEVs and/or facilitate public-private fleet collaboration as part of their climate plans. Such opportunities are also explored by Finnmark and the municipalities of Berlevåg and Båtsfjord.

In Norway, hydrogen from electrolysis is classified as a zero-emission fuel. The EU CertifHy project has developed a guarantee of origin (GoO) scheme [55]. However, HyLAW highlights the lack of a binding uniform certification of origin system at European level, which may hinder free movement of (green) hydrogen across borders. Purity requirements are defined by the *ISO 14687–2* and *SAE J2719_201511* international standards. The *AFID Directive (2014/94/EU)* states that the *ISO 14687* standard shall be followed, and this procedure is therefore not associated with any significant barrier [53], [56].

The lack of hydrogen refuelling infrastructure, on the other hand, remains a serious hindrance. Since 2017 Enova has been mandated to support HRS establishment, providing grants for up to three stations per year. The Norwegian Hydrogen Association has recommended the establishment of a network of 30 hydrogen refuelling stations (HRS) by 2022, and 50-100 HRS nationally by 2025, but the progress is slow. HRS are regulated under the *Planning and Building Act* and the *Fire Prevention Act*, with permitting requirements that basically are the same as for production or storage facilities, and not principally different from those for conventional refuelling stations (in general) and those using liquid or compressed natural gas [57], [58]. The procedure is straightforward, but the time it takes in practice may vary from 6-7 weeks and up to 2-3 years, depending on the dialogue with the municipality and

other local stakeholders [23]. 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. The above-mentioned *Guideline for tapping of dangerous substances* lists specific norms and requirements for inflammable substances and states that HRS should be designed according to *ISO/TS 20100* [47].

According to the national *Action plan for infrastructure for alternative fuels in transport*, the support for HRSs will continue. However, Enova may assess the need for further support based on the number of vehicles and give priority to larger, integrated user-cases [52].

5.3.3.6   Use: Maritime transport

As stated in the *Government's action plan for green shipping (2019)*, hydrogen is also associated with a considerable potential as alternative fuel for maritime transport, especially in a longer-time perspective [48]. Since the white paper *New emission commitment for Norway for 2030 – towards joint fulfilment with the EU*, greener shipping has been a national priority area [59]. A number of emission reduction 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), whose initial, international strategy on the reduction of greenhouse gas (GHG) emissions from ships envisages an emission reduction of at least 50% by 2050 [48].

Hydrogen and fuel cells are still considered as a relatively immature alternative for ships. However, a resolution by the Parliament in June 2016 encourages the use of development contracts for hydrogen ferries. The Norwegian Public Roads Administration runs a development project for a hydrogen-powered ferry, where construction is to be completed by 2021. 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 also strengthening the drive for hydrogen solutions.

The national *Public Procurement Act* states that where applicable, environmental criteria shall count at least 30% [60]. This has been a key driver for zero-emission ship technology. Finnmark county, where Raggovidda is located, has only four public tendered passenger routes. All of these are rather far from the wind farm. However, the coastal express trafficking the coast from Bergen up to Kirkenes has Berlevåg as a port of call. One of the two operators is introducing 3 hybrid ships, which also are prepared for possible use of hydrogen in future. Since the application of hydrogen technology for maritime propulsion only is emerging, it is not specifically regulated under the codes of the International Maritime Organization (IMO). This regulatory gap is associated with a number of barriers, which are discussed further in chapter 5.9, on the Smøla case.

While aquaculture is not present in Berlevåg today, the national *Ocean Strategy, updated in 2019*, emphasizes the huge potential in Northern Norway, as well as the need to promote blue growth via "green" technologies [61]. Figure 17 provides an overview of the areas in Finnmark where the Directorate of Fisheries has permitted present and future aquaculture activities.
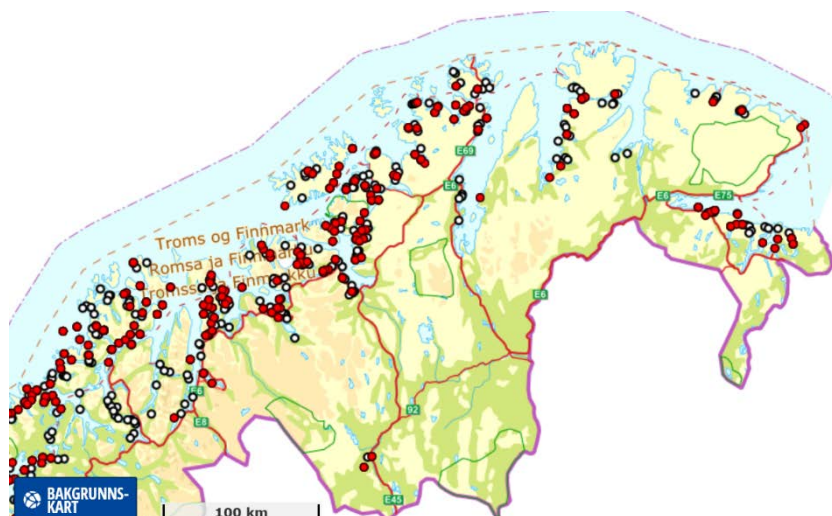
Figure 39. Areas in Northern Norway with permits from the Directorate of Fisheries, for aquaculture (fish, shellfish, or biomass). Areas with active permits are marked with red dots. Areas with expired or withdrawn permits are marked with white dots. The map is extracted from the interactive map at the Directorate's website, 05.02.2020: https://kart.fiskeridir.no/akva.

Within the aquaculture industry, hydrogen has a potential as alternative fuel for different specialized vessels (e.g. work vessels, well boats, etc.) and for heating, in addition to the use of by-products mentioned above. The largest potential, in terms of volume and emission reductions, is associated with hydrogen as fuel for maritime transport.

5.3.3.7   Use: Industry at Syd-Varanger Gruve or new industrial cluster in Berlevåg

The potential use of hydrogen for decarbonization of industry, either as in the existing Syd-Varanger Gruve or in form of an emerging industrial cluster at Berlevåg, will fall under the same regulations as production and storage of hydrogen (see above). This means that the municipality is the approval authority (if the quantity of hydrogen is less than 5 tonnes). The *Regulation for handling of inflammable, explosive and pressurized substances, including relevant installations and equipment* and the *Regulation of pressurized equipment and requirements of conformity assessment* apply [28], [39]. A guideline from the Directorate for Civil Protection *Use of dangerous substances - part I - Facilities for use of liquid and gaseous fuels*, defines how the zoning and calculation of specific safety distances are to be documented for the relevant facility, with reference to the standards NEK-EN 60079-10-01 and EIGA IGC Document 134/12/E [62].

Hydrogen is already used as input for process industry, so the legal-administrative framework is well known [23]. However, use of hydrogen as fuel will in most cases require radical process change and heavy capital investments. When it comes to industrial emissions, *the IED Directive 2010/75/EC* is implemented through the *Norwegian Pollution Control Act* and the *Regulation to restrict pollution, last amended in 2016* [63]. Measures to reduce greenhouse gas emissions are encouraged through a CO2 tax, which is increased by 5% in the national budget for 2020 and will continue to increase significantly towards 2025. There are also negotiations for a CO2 fund for the industry, where CO2 taxes payable would be channelled back into emission reduction measures. Furthermore, the state funding agency Enova offers support for energy efficiency and CO2 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 installing an electrolyser. The ongoing effort by Berlevåg municipality and Finnmark county to explore opportunities for use of

hydrogen in ØFAS for biogas production from a new waste treatment plant, may have potential in this respect. Public support may also be sought through Pilot-E, a funding scheme for largescale demonstrations where public-private partnership and committed end-users are included.

Currently, there are two projects aiming for largescale industry conversion via hydrogen in Norway, one at iron and ilmenite producer TiZir and the other at Yara. However, full pilot operation is not scheduled until 2025 and 2026, and Enova (2017) notes that individual companies have few incentives to take on such long-term investments [64]. A pilot plant for fossil-free steel production using hydrogen is being built in Luleå, as the first world-wide [65]. However, there are no such plans at Syd-Varanger Gruve, which is in a rehabilitation process and scheduled to enter full-scale operation in 2021. Replacing fossil fuels with sustainable energy sources is a long-term goal, but it is assumed that the potential use of hydrogen at Syd-Varanger Gruve in the next few years will be linked mainly to equipment, such as forklifts and heavy vehicles. The potential use of hydrogen in the present industrial cluster in Berlevåg may also be associated mostly with heavy and light vehicles. In a future low-carbon economy one may envisage new industrial activity, where green hydrogen is applied locally for production of ammonia or methanol, or as back-up fuel for power-intensive industry.

5.3.3.8 Use: Stationary power and heating in Svalbard?
The possible construction of a fuel cell power plant at Svalbard would fall under the same regulations as described for above for production and storage. A hydrogen power plant at Svalbard will require a storage capacity that exceeds 5 tonnes. This means that the national *Regulation on Control of Major Accident Hazards Involving Dangerous Substances* will apply, and a special consent from the Directorate for Civil Protection will be required. Following an initial study by THEMA consulting (2018), which concluded that a solution involving wind, solar energy and hydrogen would not be very feasible [66], Statkraft (2018) did an assessment of four alternatives for operation commencing latest by 2025, and with techno-economic calculations for the following 25 years. Here, compressed hydrogen or ammonia transported by ship from Finnmark came out as most promising [67]. The assessment assumes that the electrolyser and wind park will be integrated, and that the annual demand for hydrogen in Longyearbyen will be 3800 tonnes.

5.3.3.9 Drivers and barriers
The *New emission commitment for Norway for 2030 – towards joint fulfilment with the EU (Meld. St. Nr. 13 (2014-2015)* defined low emission solutions for transport and industry, as well as strengthening Norway's role as a supplier of renewable energy, as priority areas [57]. The national *Climate Act (LOV 2017-06-16 nr 60)* lays down ambitious climate goals: by 2030, overall GHG emissions shall be cut 45%, and those from transport 50%. By 2050, 80-95% of all GHG emissions in Norway shall be eliminated [51]. The target reported by the Norwegian Government to the EU in 2020 is to cut total GHG emission by 50% and possibly up to 55% [68]. The *White paper on energy (Meld. St. 205 (2015-2016))*, foresees a large increase in wind power generation. It also provides for increased support for research, development and implementation of hydrogen solutions and prepared the ground for a new, integrated hydrogen strategy, due in 2020 [35].

In Norway, the above-mentioned green certificate scheme is conducive for hydrogen-wind systems. However, the price for green certificates has been drastically reduced and is expected to drop towards zero over the next couple of years. In Norway no new certificates will be sold after 31.12.2021 [69]. Most of the hydrogen production initiatives so far have also benefitted from public support through Innovation Norway or Enova, but electrolysis alone is considered as a mature technology and therefore

not in the target group for some of the key public support schemes. The national *Action plan for infrastructure for alternative fuels in transport* suggests that a market for FCEVs, especially for heavy duty transport, will develop, though a target for HRS development is not specified [52]. There are also drivers for hydrogen to decarbonize heavy industry, but it will likely take some years before demand from this sector develops. However, the aim to cut 50% of the greenhouse gas emissions from local shipping by 2030, stated in the *Government's action plan for green shipping* is an important driver [48]. Together with the ongoing pilots and initiatives to introduce hydrogen through public tenders in the maritime, this indicates that there will be a market for production of larger volumes soon, which also may boost the development for hydrogen fuel cell vehicles.

The prospects for hydrogen at Raggovidda are linked to potential value chains where aquaculture, a future fuel cell powerplant on Svalbard, the local industrial cluster in Berlevåg and Sydvaranger Gruve are main users. However, there is no established aquaculture in Berlevåg municipality or near Raggovidda wind farm currently. The use of hydrogen within aquaculture is therefore dependant on the development of such industry, or transportation of hydrogen to other regions. The use of hydrogen in aquaculture is mainly related to the use of fuel for vessels. So far, hydrogen vessels for fish farming do not exist. Hydrogen powered car ferries are scheduled to enter operation from 2020-21 and fishing vessels are also under development, but it may take several years before more specialized hydrogen vessels become available [67]. Use of hydrogen in coastal shipping will also require bunkering infrastructure. This is another area where specific rules and standards do not exist. However, existing guidelines for LNG may be applied and Norway wants to take a special responsibility.

Using larger volumes of hydrogen within existing land-based industry in the region will most likely require process development and large, high-risk investments, for which stronger incentives are needed. Supplying hydrogen for heavy-duty vehicles may be more feasible but depends on the development of hydrogen refuelling infrastructure.

The potential associated with Svalbard depends on public decision-making regarding substitution of the existing coal power plant. An ammonia-based powerplant on Svalbard could provide the basis for local production of ammonia. A concept based on hydrogen could also give a large and stable demand for hydrogen from Raggovidda but depends on the development regarding on-board transportation of hydrogen. Moss Maritime, Equinor, Wilhelmsen and DNV GL recently developed the design for a bunkering vessel for liquid hydrogen, with support from Innovation Norway, but as we have seen this is an area where significant regulatory barriers remain.

In all, there are strong drivers, but also a number of legal-administrative barriers that significantly influence the prospects for full-scale development of a hydrogen-wind system at Raggovidda. The potential in a medium- to longer-term perspective appears to be very good, but it may take time for the envisaged demand to become realised. The main drivers and barriers, as well as certain key characteristics of the legal-administrative framework are summarised below (Table 38).

Table 39. Main legal-administrative drivers and barriers, as well as selected neutral to conducive core features of the institutional framework around hydrogen-wind integration at Raggovidda.

Value chain components	Drivers	Neutral, conducive	Barriers
Production & storage	• National energy policy – business development from renewables • Initial, national hydrogen strategy (2005) • Climate targets for the transport sector • Green Certificate scheme • Exemption from electricity fee • Support from local and regional authorities (climate plans)	• Municipality as one-stop shop for permitting process • Close dialogue and support from relevant authorities is reported	• Comprehensive documentation requirements • If more than 5 tonnes, special consent from Directorate for Civil Protection is required • Electrolysis defined as a mature technology and therefore falling outside certain grant schemes
Distribution	• National energy policy – business development from renewables • Initial, national hydrogen strategy (2005) • Climate targets for the transport sector • National plan for infrastructure for alternative fuels for transport (2019)	• ADR neutral, no special barriers to FCEVs • Tunnel and parking restrictions hardly applied • Interim recommendations for on-board transportation	• Restriction on trucks transporting class 2 gases on coastal ferries • Uncertainty re. hazard zones, ventilation, safety requirements for gaseous and liquid hydrogen onboard ships • Lack of specific regulation for on-board transport of hydrogen
Use: flexibility services	• Ongoing process to implement the Clean Energy Package, and the EU Guidelines for System Operations and Energy Balancing • NEM regulation opens for flexible production agreements	• Licence to build and operate must be granted from RME • Trading license from the same directorate is required	• Lack of incentives • Non-discriminating grid tariffs • Special tariffs for flexible use only available in some regions, others not
Use: maritime transport	• Active use of innovative, green public procurement • Several funding schemes	• Alternative Design as opportunity for innovative co-development • Class rules for fuel cell systems available • Maritime Authority keen to facilitate	• Lack of specified procedure for design/type approval • Lack of specific standard for hydrogen bunkering installations • Special consent from Directorate for Civil Protection required for all permanent onshore bunkering facilities

Value chain components	Drivers	Neutral, conducive	Barriers
Use: road transport	• One of Europe's best incentive schemes for FCEVs • Hydrogen categorized as zero-emission fuel • Active use of innovative, green procurement • H2 included in National plan for alternative fuels in transport • Grant support for HRS	• Individual and type approval harmonized with EU • ADR – no special barriers regarding FCEVs	• Lack of refuelling infrastructure • Continued support for HRS, but depending on development in (heavy) vehicles • Strong focus, priority on BEVs and biofuels
Use: industry	• CO2 tax • Process to establish CO2-fund • Available funding/risk reduction schemes; Pilot E, support from Enova and Innovation Norway	• Hydrogen already well established in industry • Regulated as an industrial chemical	• Lock-in to fossil processes • Individual solutions, implementation of immature technology • High financial risk • Lack of incentives

5.4 Smøla Case Study

Smøla is an island located in the western part of Norway and close to the coastline. It is a small municipality with a population above 2000 persons and 1,154 employees. Table 40 shows how the employees are distributed by industries. We see that workers are distributed in all industries except crude oil, and that Smøla public administration and other services plays an important role in the local community.

Table 40. Number of employees by industry Smøla.

Municipality Smøla	Employees	
Agriculture. forestry and fishing	333	28.9 %
Crude oil and natural gas. extraction and pipe transport	0	0.0 %
Industry and mining	121	10.5 %
Power and water supply	15	1.3 %
Construction	64	5.5 %
Wholesale. hotel and restaurant activities	122	10.6 %
Transport and communication	87	7.5 %
Finance and business services	62	5.4 %
Public administration and other services	337	29.2 %
Unknown	13	1.1 %
Total	1,154	

The total expected hydrogen output from the factory in Smøla is estimated to vary between 365 tonnes and 730 tonnes. In Figure 40, we show two potential sites for hydrogen plants in Smøla are located. In site 1 they expect a production capacity of 365 tonnes or one tonne each day, whereas the production

capacity is double as high in site 2. They expect economics of scale on the sites, average costs on site one is 47NOK/KG H2, while it is 27NOK/KG H2 for the second. Energy costs make round 60 % of the production costs and equipment is the second largest cost contributor round 25%.
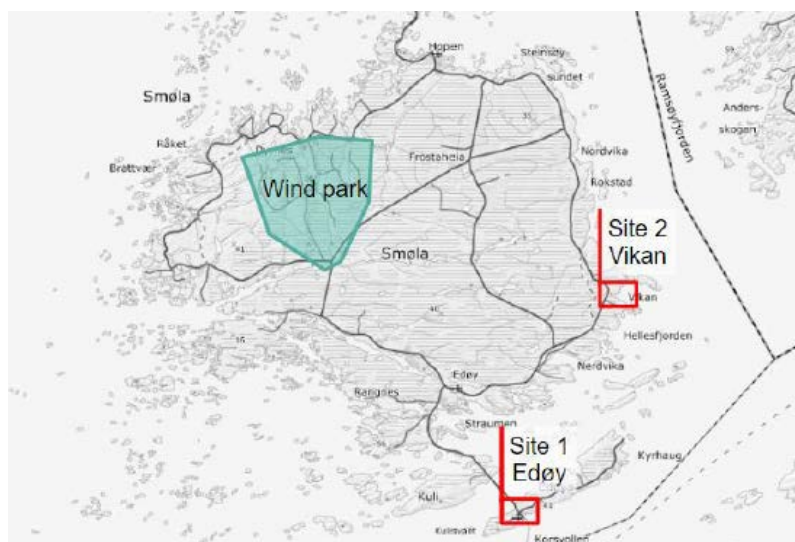
Figure 40. Two potential sites of hydrogen plant in Smøla.

5.4.1 Upstream spillover industrial job effects

We do not have detailed data on investments and operating costs in this case. Thus, based on average costs and expected capacity, we connect this case to the detailed data we have from Raggovidda. The location on site 1 is comparable to the data we have from the Raggovidda case. Raggovidda expected to produce 390 tonnes while site 1 in Smøla will produce 365 tonnes. Thus, in the investment phase we could expect local job effects for the municipality Smøla of about 9 employees. This is a high scenario estimate where we assume that the electrolyser is supplied from a local company. In the operating phase the local effects for the municipality Smøla is estimated to about 4 employees. We have not estimated this case in the PANDA model, because the industry structure is not very different in the two regions and given the uncertainty of these numbers this is a reasonable simplification.

Although the location on site 2 in Smøla has double the production capacity as site 1, we do not expect much larger effects for job creation. The excepted economics of scale by doubling the production capacity offset higher purchases linked to higher production volumes. Hence, we could expect higher job effects in site 2 than site 1, but they will be only minor.

5.4.2 Downstream spillover industrial job effects and other local job effects

The hydrogen produced by the site in Smøla is expected to be demand by lorries, rail, other maritime, cars, bus and high-speed ferries. Figure 41 shows the estimated hydrogen demand in the Smøla case, in a so-called High case scenario towards 2050. Demand by rail, lorries, cars and buses will not generate any large number for local jobs in Smøla. However, hydrogen demand by other maritime industry and high-speed ferries may lead to establishment of new ocean-based industrial activity that could generate additional jobs for the local economy.

One example of local job effects is that in site 2, [14] expect that 16.8 tonnes oxygen is produced daily, where this oxygen could be used by a hatchery. Based on an oxygen demand estimates by hatcheries, this amount of oxygen corresponds to the demand of a hatchery producing 12,000 tonnes fish yearly. With 403 employees working in hatcheries in Norway producing about 46,100 tonnes of fish yearly, a

rough estimate of local job effects from a hatchery producing 12,000 tonnes, will be around 100 employees[11]. This estimate is rather optimistic, considering that the total hatchery production in Norway is 46,100 tonnes, and the expected potential must be seen in the context that this is an industry which is heavily regulated in Norway.
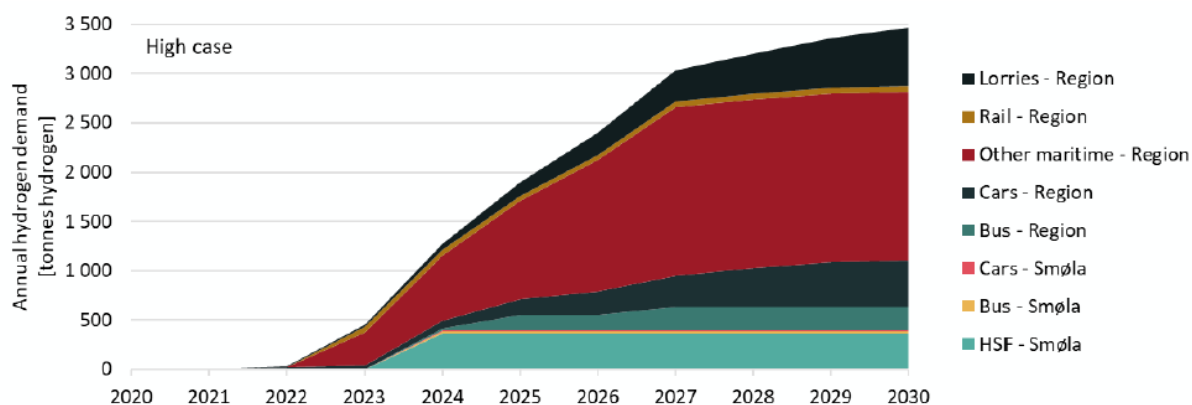
Figure 41. High scenario of Hydrogen demand in Smøla[12].

Additional tax income from a wind-hydrogen system affects number of local public jobs and local public economy positively. Statskraft is the company responsible for operating the wind-park in Smøla. Smøla municipality has not any ownership in this company. Hence, in contrast to Berlevåg municipality, Smøla municipality does not expect any additional future surplus income from the wind-park. On the other side, the real estate tax income from the wind-park is considerable for the municipality, 8.7 mill NOK in 2019.

5.4.3 Legal-administrative drivers and barriers

This section addresses regulations, codes and standards, as well as drivers and barriers for the value chain activities associated with a hydrogen-wind system at Smøla. The two alternatives considered for the Smøla case implicate regulations regarding production, storage, distribution and application in maritime as well as road and railway transport (see Figure 42). Thus, the value chain includes several of the same components as in the Raggovidda case.

---

[11] https://www.fiskeridir.no/Tall-og-analyse/Statistikkbanken.
[12] Vandenbussche, V., et. al. SMØLA HYDROGEN VALUE CHAIN PROJECT FOR MØRE AND ROMSDAL COUNTY COUNCIL (NORWAY), WITH SUPPORT BY INTERREG NORTH SEA REGION, Endrava, 2019.
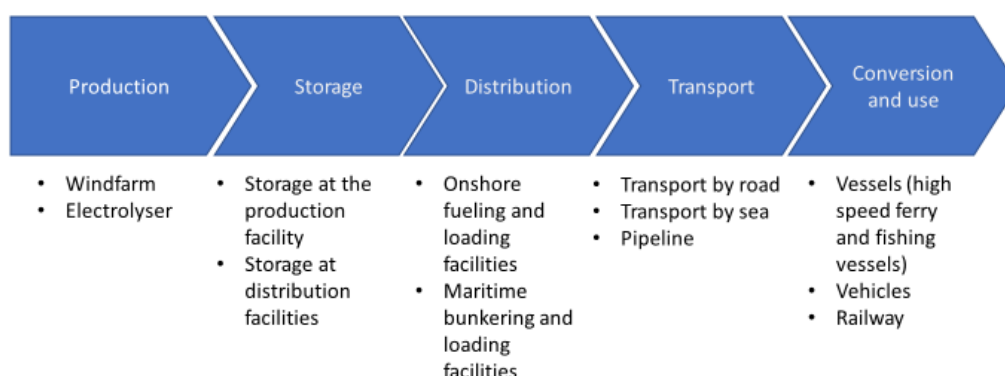
Figure 42. Assumed potential value chain – Smøla.

The prospects for a hydrogen production unit integrated with the existing wind farm at Smøla depend on the development of a demand for hydrogen in maritime and land transport. At present, the potential main user is a high-speed passenger vessel trafficking the area. It is estimated that the maximum bunkering capacity per trip for this vessel will be approximately 1.2 tonnes. In addition, a future demand from hydrogen fuel cell buses, trucks and other fleet vehicles in local transport may be foreseen, based on the national climate targets for the transport sector and limitations associated with biofuels and battery technology in a 2050 perspective [71]. The inland railway line Raumabanen, also in Møre and Romsdal county, is another potential user. Raumabanen is one out of three remaining railways in Norway that are operated by diesel trains. The possibilities for introducing and testing hydrogen fuel cell trains on this stretch was recently explored under the Interreg North Sea Region project G-PaTRA (Green Passenger Transport in Rural Areas) [72]. The estimated demand for hydrogen if both passenger and freight transport on the railway continue according to the same schedule and volume range as today is between 260 and 350 kg/day.

5.4.3.1   Establishing production

The establishment of an electrolyser connected to the wind farm at Smøla will be subject to the same regulations as for the Raggovidda case (see section 5.5). A feasibility study carried out by Norsk Vindenergi Senter (NVES) considers two production alternatives: 1) Production at Edøy, which is a port of call for public tendered ferry and passenger vessels and potential site for a hydrogen bunkering station, a few km away from Smøla wind farm, and 2) Production within the wind farm, "behind the meter" and therefor with lower cost of electricity [73]. Since the foreseen production volumes for both alternatives are less than 5 tonnes, the *Regulation on Control of Major Accident Hazards Involving Dangerous Substances* will not come into play, and the municipality will be the permitting authority both when it comes to land use planning and permission to operate. If all necessary documentation is provided correctly, the process to obtain the permit should take maximum 42 weeks.

There might be differences between the two alternatives in terms of safety requirements. Alternative 1, with production at the existing ferry port, may involve challenges in terms of space and safety distances relative to other facilities, such as the local culture centre and bus stop at the terminal. However, a location linked to existing industrial activity (mechanical workshop, boat seller) and hence in a defined industrial zone could make it easier. With alternative 2 additional el safety requirements

may apply (as noted in section 5.5, for Raggovidda). A full environmental impact assessment (konsekvensutredning) has already been carried out for the wind farm.

In the case of alternative 1, the production plant must be connected to the e-grid. This implies that a grid tariff must be paid and the development regarding grid tariffs will influence future production costs. With alternative 2, this uncertainty may be avoided.

5.4.3.2   Storage

Storage of hydrogen in the Smøla case will be subject to the same regulations as for the Raggovidda case (see section 5.5). None of the two alternatives considered by NVES involve storage of 5 tonnes hydrogen or more. Thus, it may not be necessary to apply for special consent from the Directorate for Civil Protection in the initial phase. Towards 2030, upscaling to meet demand from multiple maritime users are envisaged. In a longer-term perspective, special consent may thus be required, and the requirements associated with the *Regulation on Control of Major Accident Hazards Involving Dangerous Substances* must be met [32].

5.4.3.3   Distribution

The distribution of hydrogen in the Smøla case involves either road transport, using specialized tube trailers, and/or distribution via onshore pipelines. Alternative 2 includes construction of a pipeline (approximately 1000 m) for compressed hydrogen at 350 bars from the production facilities to the tanks at the bunkering/refuelling station. Alternative 1 implies that the hydrogen is compressed to 350 bars at the production site, and then transported by truck to the local bunkering /fuelling station, as well as to other locations in the region. This alternative does also include a potential expansion of the facility in future, including a 250 m pipeline for transporting hydrogen to a nearby bunkering station (not intended for the high-speed passenger vessel). None of the two alternatives imply that the hydrogen volume present in production, storage and distribution facilities will be 5 tonnes or more. This means that it may not be necessary to apply for consent for the storage facilities.

A pipeline system will be regulated the same way as pipelines for natural gas, under the *Regulation on handling of inflammable, reactive and pressurized substances and equipment and facilities used in the handling of such substances* [28]. A special *Guideline for the transport and distribution of petroleum in onshore pipelines,* issued by the Directorate for Civil Protection, specifies the requirements and procedures for class 2 gases, including hydrogen [74]. Pipelines carrying pure hydrogen requires addressing a number of specific issues, including the potential for embrittlement of some steels and sealing difficulties at fittings that are tight enough to prevent natural gas from escaping, but possibly not hydrogen.

Truck transportation of hydrogen will fall under the national *Regulation of land transport of dangerous goods,* and *Regulation of transportable pressure equipment*, as described in section 5.5. for the Raggovidda case [41], [42].

5.4.3.4   Loading and bunkering facilities

Onshore loading installations at Smøla will be subject to the same regulations as for the Raggovidda case (see section 5.5). The overarching regulatory framework is already established, in the *Regulation on handling of inflammable, reactive and pressurized substances and equipment and facilities used in the handling of such substances*, and the *Guideline for tapping of dangerous substances* [28], [47].

As noted above, the *Government's Action Plan for Green Shipping (2019)* states that Norway will take a special responsibility when it comes to bunkering stations [48]. An application for special consent from the Directorate for Civil Protection will be required for all onshore hydrogen bunkering infrastructure, regardless of volume and number passengers. This implies that the risk assessment for stationary bunkering facilities shall include quantitative analysis showing risk contours [33]. For bunkering from trucks, quantitative assessment is not required, beyond the calculations needed to determine the inner hazard zone.

5.4.3.5   Use: Maritime transport

Both the two alternative set-ups considered for Smøla assume that the hydrogen-wind system will supply a high-speed passenger vessel connecting the island to the mainland and nearby island Hitra. A zero-emission vessel is currently being constructed under an innovative competition contract granted by Trøndelag county in collaboration with other county councils, including that of Møre and Romsdal. This initiative is motivated by the national climate targets and increasing emphasis on green public procurement noted in section 5.5.

Maritime activity is for a large part regulated via international conventions and codes set by IMO. The *International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code)* was updated in 2017 to address low-flashpoint fuels such as liquid natural gas (LNG). This code is transposed into Norwegian legislation in the *Regulation on ships using fuel with a flash point below 60°C* but does not include specific requirements for the design and operation of hydrogen fuel cell vessels [75]. This regulatory gap implies that the type approval of new designs falls under the international *Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments (MSC.1/Circ.1455).* To address the uncertainties and multiple concerns involved in the development and implementation of new technologies, these guidelines define a process consisting of five steps: 1) development of a preliminary design, 2) approval of preliminary design, 3) development of final design, 4) final design testing and analyses, and 5) final approval. The applicant must either compare the innovative design to existing designs to demonstrate an equivalent level of safety or carry out a risk analysis of the alternative design compared to overall risk evaluation criteria [76].

The consequence of the lack of specific regulations for hydrogen ships is that the application process is time consuming and expensive for the developers. Use of specialized consultants and broad stakeholder involvement is required, and there are remaining questions regarding several aspects, such as the requirements for pressure tanks, air release from fuel cells and impact of sea spray and vibration on risk events where fuel tanks are mounted on top deck. When it comes to zoning a main reference is IEC 60079-10-1. While actors call for specific rules and standards, regulators and risk/safety experts emphasize the need for dialogue and tend to favour function-based requirements, given that the technology still is under development. More specific guidelines and standards are under development, but this will take time given the decision-making procedures of the IMO. Some of the international classification societies have developed class rules for the application of fuel cells, but not for the whole hydrogen fuel systems.

Beside the initial high-speed passenger vessel, the coastal express and aquaculture in the region are potential users in a medium and longer-term perspective. The maritime industry in Møre and Romsdal county has a stake in this development, where amongst other shipyard Fiskerstrand has an ongoing project to retrofit an existing ferry with a hydrogen fuel cell propulsion system. As depicted in Figure 40, the region around Smøla has an even higher density of current and permitted aquaculture facilities

than Northern Finnmark, and there are ongoing projects to explore the potential synergies with hydrogen-wind systems, carried out with regional development support from the regional authorities.
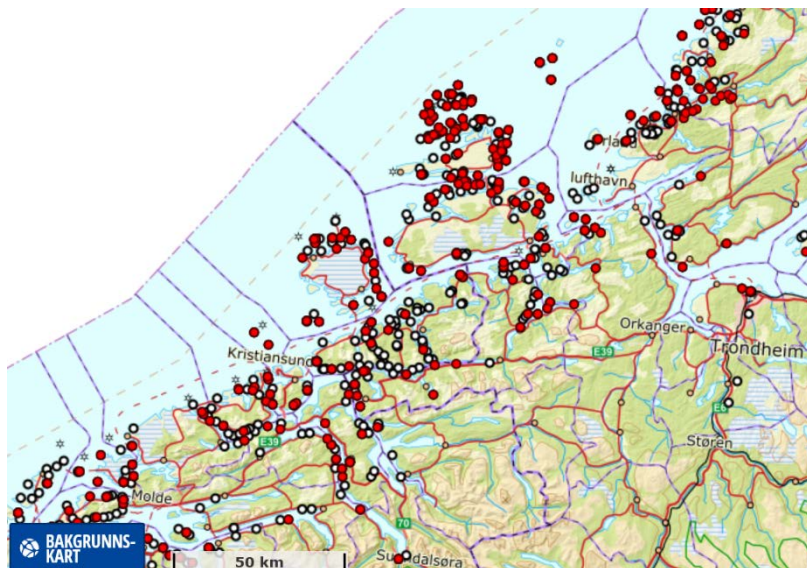

Figure 43. Areas in Møre and Romsdal and southern Trøndelag with permits from the Directorate of Fisheries, for aquaculture (fish, shellfish, or biomass). Areas with active permits are marked with red dots. Areas with expired or withdrawn permits are marked with white dots. The map is extracted from the interactive map at the Directorate's website, 05.02. 2020: https://kart.fiskeridir.no/akva.

5.4.3.6   Use: Road transport

Both local buses, trucks and other fleet vehicles are considered as potential users at Smøla, as well as in Raggovidda. The regulatory framework for these applications is also the same, with the procedures, drivers and barriers discussed for road transport in section 5.5. It should be noted, however, that Smøla is located closer to existing hydrogen refuelling stations and the basic network of 30 stations recommended by the Norwegian Hydrogen Association.

Møre and Romsdal, together with three other counties, has defined a hydrogen strategy for Western Norway which emphasizes the potential for local/regional deployment of gaseous hydrogen, especially in road transport where solutions are commercially available [77].

5.4.3.7   Use: Railway

The Rauma railway is another potential user in the region, and the rail hub of Åndalsnes is regarded as a suitable location for future refuelling infrastructure. Fuel cell hydrogen trains have been tested in Germany since 2018, and Norway is among the nations that have been looking into the possibility to replace diesel trains on non-electrified stretches. In France, the government wants the first hydrogen train to be on the rails by 2022, and the interest is high also in other European countries such as France, Germany, Italy, Denmark, and the UK.

Transport of dangerous good on railways is regulated under the *ADR/RID regulation of 1 April 2009, no. 384,* which implements the *European Agreement on the International Carriage of Dangerous Goods by Road (ADR*) and the *European Agreement on the International Carriage of Dangerous Goods by Rail (RID) (Règlement concernant le transport international ferroviaire des marchandises dangereuses)* in Norway [78]. The Annexes to the ADR and RID Agreements are updated at regular intervals (usually every two years). The European Commission incorporates each time the new publications in the form

of a Directive. Still, there are no specific European regulations for hydrogen trains and the necessary infrastructure. The lack of regulation and permitting procedures is considered as a serious barrier to fuel cell hydrogen trains [79].

In Norway, a recent report from the Directorate for Railways concludes that a hybrid solution with on-board batteries and part-electrification will be the recommended alternative for replacement of our fossil fuel trains [80]. Thus, limited political acceptance due to high costs and competition from battery-electric solutions seems to be the main institutional barrier right now.

5.4.3.8 Drivers and barriers

The national climate policy and ambitious targets for reducing GHG emissions are main drivers for integrated hydrogen-wind generation at Smøla, as at Raggovidda. The *White paper on energy*, with its emphasis on market-based development of renewable energy and promise of an integrated national hydrogen strategy is another important influence, in addition to the green certificate scheme facilitating renewable energy production. In the case of Smøla and indeed Møre and Romsdal as a whole, there are synergies between these factors, the national *Maritime strategy*, of 2015, and the *Government's Updated Ocean strategy (2019)*, which emphasize the need to reduce GHG emissions as well as the need to promote local value creation in order to reduce the vulnerability of regional business communities and strengthen the adaptability of the regions[61], [81]. As noted above, the county council has been an active promoter of hydrogen technologies, especially for application in the maritime sector.

The *Regional hydrogen strategy*, developed with the other counties in Western Norway (from 1ged into one county: Vestland) is associated with a wide range of project activities and advocacy [77]. Green public procurement, including competitive innovation contracts, has been an important driver for hydrogen fuel cell and other zero-emission solutions for maritime transport. At the same time, the ongoing maritime projects are targeted by several competing initiatives along the coast of Western Norway, including electrolysis linked to wind and hydropower, as well as the production of hydrogen based on steam methane reforming with carbon capture and storage (CCS) at Tjeldbergodden, also in Møre and Romsdal [23].

At the current stage, the prospects for hydrogen-wind production at Smøla seem to depend, to a large extent, on the development regarding the high-speed passenger vessel that is under development and future decisions by the relevant county councils regarding public tendered ferry and passenger transport. In a slightly longer-term perspective, there is the potential for hydrogen deployment in aquaculture, which has a stronghold in the region around Smøla. However, the lack of a standard procedure for design type approval of hydrogen fuel cell ships is a serious barrier, in that the procedure for Alternative Design is time-consuming and adds cost, as compared to battery-electric and biofuel-based solutions. Procedures and guidelines for hydrogen bunkering facilities are also lacking in the moment, and the requirement for special consent has further implications when it comes to costs and competence/assessment requirements.

Green public procurement may also facilitate introduction of FCEVs, for heavy duty as well as passenger transport. However, the current lack of refuelling infrastructure is a critical factor. The national *Action Plan for infrastructure for alternative fuels in transport (2019)* confirms the intention to support HRS roll-out [52] but the lack of specific targets combined with a recent explosion and

historical ups and downs in the implementation of HRS in Norway leave a level of uncertainty which currently has put a break to the increase in number of FCEVs and HRS projects.

The case of Smøla appears more mature than Raggovidda, in the sense that demand for a substantial volume of hydrogen may be realised through the high-speed hydrogen passenger vessel in near future. It is also in a regional context with established institutional capacity, in the form of competence, networks and ongoing projects to do with hydrogen, and it is associated with uses and users that are rooted in the region and can be influenced by local and regional decision-makers. The main drivers and barriers, as well as certain key characteristics of the legal-administrative framework are summarised in Table 41.

Table 41. Main legal-administrative drivers and barriers, as well as selected neutral to conducive core features of the institutional framework around hydrogen-wind integration at Smøla.

Value chain components	Drivers	Neutral, conducive	Barriers
Production & storage	• National energy policy – business development from renewables • National climate targets, decarbonization of transport • Green Certificate scheme • Exemption from electricity fee Support from local and regional authorities (regional development, hydrogen strategy)	• Municipality as one-stop shop for permitting process Close dialogue and support from relevant authorities reported	• Comprehensive documentation requirements • If more than 5 tonnes, special consent from Directorate for Civil Protection is required Electrolysis considered as mature technology, thereby barred from some support schemes
Distribution	• National energy policy – business development from renewable energy • Initial, national hydrogen strategy (2005) • National climate targets for the transport sector National plan for infrastructure for alternative fuels for transport (2019)	• ADR neutral, no particular barriers to FCEVs • Tunnel and parking restrictions hardly applied • Interim recommendations for on-board transportation of hydrogen Guideline for petroleum in onshore pipelines (specifies requirements for class 2 gases)	• Restriction on trucks transporting class 2 gases on coastal ferries Uncertainty re. hazard zones, ventilation, safety requirements for gaseous and liquid hydrogen onboard ships
Use: maritime transport	• National climate targets • IMO initial climate strategy • Green Public Procurement, innovation contracts • The Government's action plan for green shipping (2019) • Multiple funding schemes Maritime strategy (2015) emphasizing sustainable innovation	• Alternative Design as opportunity for co-development • Maritime Authority keen to facilitate	• Lack of specified procedure for design/type approval • Lack of specific standard for hydrogen bunkering installations Special consent from Directorate for Civil Protection required for all permanent onshore bunkering installations

Value chain components	Drivers	Neutral, conducive	Barriers
Use: road transport	• One of Europe's best incentive schemes for FCEVs • Hydrogen categorized as zero-emission fuel • Active use of innovative, green procurement • H2 included in National plan for alternative fuels in transport Grant support for HRS	• Individual and type approval harmonized with EU ADR – no special barriers regarding FCEVs	• Lack of refuelling infrastructure • Continued support for HRS, but depending on development in (heavy) vehicles • Strong focus, priority on BEVs and biofuels As of yet, there is no whole vehicle EU or national type approval available for trucks
Use: railway	• Target of zero emissions from railways by 2030 FCH trains are area of governmental priority in France, Germany, and UK	ADR/RID regulation of 1. April 2009, no. 384, implementing ADR and RID (Règlement concernant le transport international ferroviaire des marchandises dangereuses)	• Strong focus on electrification • FCH trains currently not governmental priority in Norway No specific European regulation for hydrogen trains and the necessary infrastructure

5.5 Moncayuelo Case Study (information from TECNALIA)

The location of Moncayuelo wind farm is shown in Figure 44. The windfarm (white line) is enclosed by several municipalities (yellow dots). These municipalities are Tafalla, Olite, Beire, Pitillas, Caparroso, Marcilla, Peralta, Falces and Miranda de Arga. The population and number of employees in the corresponding municipalities are shown in Table 42 [13].

Figure 44. Location of wind-hydrogen system in Moncayuelo region in Spain.

[13] Data sources: https://www.bvdinfo.com/en-gb/our-products/data/international/orbis, https://www.ine.es/FichasWeb/Welcome.do.

Table 42. Population and employees in the municipalities [14].

Data and Activity Sectors	Tafalla	Olite	Beire	Pitillas	Caparroso	Marcilla	Peralta	Falces	Miranda de Arga
Population (nº inhabitants 2018)	10,605	3,931	275	493	2 702	2,862	5,823	2,306	850
Extension (km²)	834.70	83.20	22.25	42.30	80.80	21.90	88.40	114.89	60.1
Employees by industry									
Industry	76	40	21	24	13	19	95	19	44
Construction	117	42	21	24	19	24	37	18	44
Commerce, transport and hospitality	291	130			66	72	146	62	
Information and Communication	9	.			.	.	.	.	
Financial and insurance activities	11	.			.	.	.	.	
Real State Activities	19	.			.	.	14	.	
Professional and technical activities	126	.			.	.	71	.	
Education, health and social services	39	.			.	.	27	.	
Other personal services	58	.			.	.	43	.	

The municipalities such as Tafalla, Olite and Peralta have a more diversified industry structure than the other surrounding municipalities, and with an industry structure with more specific sectors that potentially could benefit from hydrogen production in the area.

The socio-economic effects will vary according to the size of the installed electrolyser. The size of the installed electrolyser in the Moncayuelo case varies between 2.5 and 10MW in different business cases. In the socio-economic analysis we consider the effects of a similar electrolyser (producing 2.5MW) as installed in the Raggovidda case. As we do not have any available supplier data for the operating and investments phase in the Moncayuelo case, we must convert and scale the data from Raggovidda to fit this case. The results of the fitted data are presented in Table 43.

Table 43. Investments and operating costs for the Hydrogen Plant in Moncayuelo (arbitrary data).

Hydrogen Plant (measured in EURO, 2018)		
Investments phase		**Supplier Industry**
Buildings	727,202	Construction (Local)
Fiber	28,374	Electricity. gas. steam and air conditioning supply (Local)
Transformer	48,867	Manufacture of computer. electronic and optical products and electrical equipment (Local)
Consultants	45,507	Repair and installation of machinery and equipment (Local)
Electrolyser	1,477,833	Manufacture of computer. electronic and optical products and electrical equipment (Local/National/Foreign)
Operating phase		**Supplier Industry**
Power (assumption 37.6€/MWh)	712,167	Electricity. gas. steam and air conditioning supply (Local)
Maintenance	29,320	Repair and installation of machinery and equipment (Local)
Output (assumption 308 tonnes pr. year, estimated energy use 17 GWh)	1,050,739	

5.5.1   Industrial job effects in Moncayuelo case

We implement the data in Table 43 into the Norwegian I-O model PANDA in an arbitrary municipality in order to see the employment effects of the hydrogen plant. As the electrolyser and outputs of hydrogen in the Moncayuelo case almost is equal to the one in Raggovidda, we expect that the in the investment phase local effects for the municipalities of about 9 employees and 4 employees in the operating phase. For the potential of new industrial jobs connected to local use of hydrogen in the region, we refer to the previous discussion done for Raggovidda and Smøla.

With respect to other local socio-economic effects, Moncayuelo (48MW, 32 turbines) wind farm is fully owned by Acciona[15], therefore we do not expect any additional municipal tax income from future operating surplus of the wind farm. On the other hand, Moncayuelo together with Vedadillo (49.5MW, 33 turbines) and the experimental area of Vedadillo (9MW, 3 turbines) are all located in the municipality Falces. According to the public budget of Falces[16], the municipal budget of Falces is about 3 million euros with a third coming from the wind activity tax. With these references, it could be considered that about 0.45 million euros could be assigned to the Moncayuelo wind farm contribution to that wind activity tax financing local public jobs.

---

[15] https://www.thewindpower.net/owner_es_114_acciona-energia.php, https://www.thewindpower.net/windfarm_es_2065_moncayuelo.php.

[16] https://www.energias-renovables.com/eolica/el-pueblo-navarro-de-falces-premio-aee-20150616.

5.5.2 Legal-administrative drivers and barriers

In Spain, as in Norway, hydrogen is regulated as an industrial chemical. The *SEVESO* and *ATEX Directives*, together with *Directive 2010/75/EU in industrial emissions* constitute the umbrella legislation [82]. For the case of Moncayuelo, the authors of this section have not had any direct contact with the stakeholders. Based on general information regarding the energy situation in Spain and the findings reported in HyLAW we assume a potential value chain where distribution is done mainly via road transport and the largest potentials for deployment are in road transport, flexibility services and gas grid injection. Deployment of hydrogen for decarbonization of existing industry and as alternative fuel for the Spanish fleet are also associated with considerable potential in a long-term perspective. Thus, a potential value chain may be depicted as in Figure 46.
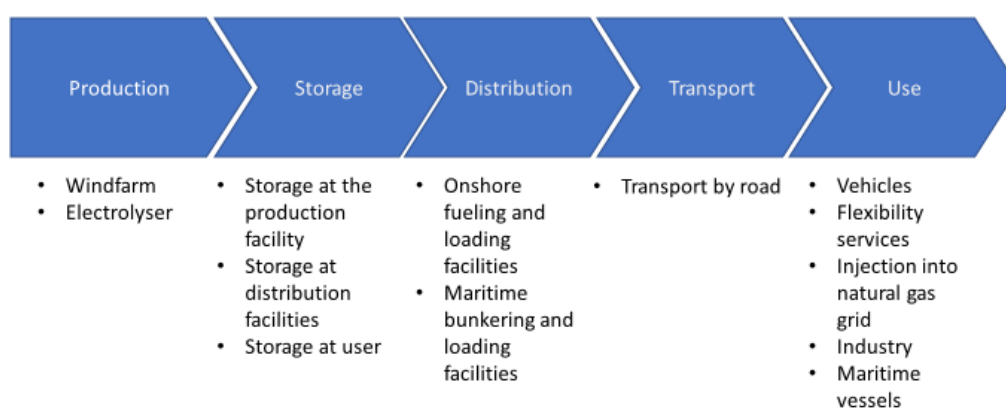
Figure 45. Potential hydrogen value chain, Moncayuelo.

In the following, regulations, codes and standards for the respective value chain activities are discussed.

5.5.2.1 Production

According to the mapping in HyLAW, the prospective hydrogen producer in Spain must interact with several different authorities. A hydrogen plant 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:

1. Development of project.
2. Consultancy to competent authority regarding viability of the project.
3. Development of construction plan and application for licences.
4. Urbanistic inform from city council.
5. Application for Integrated Environmental Authorization from the competent regional authority.
6. Obtainment of business activity licence from city council.
7. Authorisation for electricity and water supply.
8. Authorisation from the Provincial Industry Service.

There may be slight variation across the Autonomous Regions, in how the procedure is administered, but the Integrated Environmental Authorisation (*AAI, Autorización Ambiental Integrada*) should be

equivalent [75]. No minimum level of hydrogen production capacity is given. This means that all industrial hydrogen production facilities are considered on the same regulatory basis. The procedure is considered as a barrier, due to lack of specific legislation for hydrogen and the number of permits that must be obtained. If the facility will harbour 5 tonnes of hydrogen or more, the requirements associated with the SEVESO Directive also come into play.

The procedure for connecting to e-grid 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 of obtaining the access permit, and connection permit. If the connection is high- or medium-voltage, the TSO Red Eléctrica de España (REE) is the responsible authority. If the connection is for low voltage, the DSO is in charge. Law 15/2012 established a tax on the sale of electricity at a rate of 7% on the total revenues accruing to generators from the electricity generated and incorporated into the grid by each of their facilities [83].

Paralleling the development in Norway, 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), in line with Directives 2009/72/CE and 2009/73/CE. The CNMC has already proposed a new regulation on access and connection to the grid which is currently being studied and is foreseen to be approved in 2020 [84].

5.5.2.2   Storage
The regional government is responsible for the storage permitting process, which is regulated under the *Royal Decree 656/2017 – Regulation of Storage of Chemical Products and its Complementary Technical Instructions.* The procedures for approval of hydrogen storage facilities are not different from the procedures for storage of other inflammable gases and do not distinguish between small, commercial and largescale industrial storage [85][90]. The stakeholders consulted in HyLaw saw this as a medium severity barrier since industrial storage requires either a simplified or a full EIA. The environmental protection obligations associated with the storage (and possible leakage) of chemical products are automatically applied to hydrogen, despite the minimum risk of environmental damage as a result of its possible leakage or discharge.

5.5.2.3   Distribution
Transport of hydrogen in Spain 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 [86]. Transport by road is further regulated by *ADR European Agreement concerning the international carriage of dangerous goods by roads* [87]. 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 [88]. There are no specific requirements on national level for transportation of hydrogen, in terms of roads, specific routes, and vehicles, and the approval processes are the same as for other class 2 gases.

Transportation of hydrogen on board ships does not seem very relevant for Spain presently. However, 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 [89]. The *IGC Code* [44] and set of *Interim recommendations for carriage of liquefied hydrogen in bulk (MSC.420 (97))* [45] would therefore also apply in Spain.

5.5.2.4 Use: Road transport

Spain's draft National Energy and Climate Plan (NECP) sets a GHG emission reduction target of 43.5% (compared to 2005) by 2030 for the transport sector, and foresees that by 2040 all new cars sold will be zero-emission vehicles [90]. 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. Hydrogen fuel cell electric vehicles are registered as zero-emission cars. The technical inspection body is Inspección Técnica Vehicular. There are no specific requirements for FCEVs, but a point of concern for the stakeholders consulted under HyLAW was the training of technicians for Vehicle Technical Inspections. Vehicles are increasingly complex and have more systems, such as high voltage batteries. The combination of these and the storage and use of compressed gas in FCEVs, may require a greater degree of specialization by these professionals.

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 FCEVs 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€ [91]. As part of the NECP, low-emission zones will be established in cities above 50,000 inhabitants. Policies for the uptake of zero- and low-emission cars are also found at regional and local level, as part of local mobility strategies [92]. According to the National plan for alternative fuels infrastructure, Spain aims to have 500 hydrogen fuel cell vehicles by 2020.

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 [93]. A main concern is that certification of impurities is very restrictive and there is no accredited entity to certify the quality of hydrogen as fuel. The application for permission to establish and operate HRS should be very similar to the applications to establish conventional fuel stations. However, there is no dedicated regulation or procedure for establishing an HRS. It has to be considered as a combination of production, storage and public sales of hydrogen and the resulting process is very complex [94]. Still, 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)* [95], 20 publicly accessible hydrogen refuelling points are foreseen by 2020. The plan contains an extensive list of measures, most already in place [96].

5.5.2.5 Use: Maritime transport

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)* [97] is ratified in Spain, where *Directive 2014/90/EU on marine equipment* [98] and *Directive 2009/45 on safety rules and standards for passenger ships* [99] transpose the overarching IMO conventions. The lack of specific regulations for hydrogen is associated with a high-severity barrier, but there is limited experience so far and this application does not appear to particularly relevant for Moncayuelo presently.

5.5.2.6 Use: Flexibility services, injection of electricity

Spain has a target to increase the share of renewables in electricity production to 74% in 2030 [100]. One of the important functions foreseen for hydrogen in Spain is that it may help reduce the risk of over-investment in energy infrastructure by facilitating local storage and use of renewable energy. A new auction system has been established to allocate an interruptibility service, which is used a demand

management tool to provide a rapid and efficient response to electricity system needs (system security or reduction of costs). This service is activated in response to a power reduction order issued by Red Eléctrica to large consumers that are providers of this service, and that are mainly large-scale industry. According to HyLAW, an electrolyser must offer an interruptible demand of at least 5MW to qualify for the interruptibility service and cannot participate in other flexibility mechanisms [95]. However, this project ended in 2018.

The Royal Decree 244/2019 regulates the administrative, technical and economic conditions for the self-consumption of electricity [100]. 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. When there is a self-consumption with surpluses, i.e. possible to inject surplus energy into the distribution networks, the installation may voluntarily benefit from a surplus compensation mechanism as long as it complies with certain conditions. At the same time, self-consumed energy of renewable origin is exempt from all types of charges and tolls. According to the HyLAW report for Spain, fuel cells are not considered as sources of generation within the special regime of renewable energy, cogeneration and waste. They can be registered as producers, but according to *Royal Decree 413/2014, regulating electricity generation activity using renewable energy sources, cogeneration and waste*, they cannot be defined as renewable or cogeneration and are therefore not eligible for the toll exemptions [95]. According to a recent assessment, fostering the industrial services linked to the self-consumption is one of the foreseen changes in Spanish electricity regulation in the medium and long term. The recent approval of *Directive (EU) 2019/944* and *Regulation (EU) 2019/943*, will also imply changes to keep fostering decarbonisation of the energy system and competition by granting consumers more rights and easing their participation in the market [84].

5.5.2.7   Use: Gas grid injection

Hydrogen-wind systems could be one solution contributing to a future "greening" of Spain's gas grid, which consists of 87,699 km of pipelines. The *Gas Directive (Directive 2009/73/EC)* constitutes the overall regulatory framework for hydrogen injection into the gas grid within the EU [101]. However, this framework has been drawn up around natural gas, with quality standards based on gas calorific value. The volumes of hydrogen allowed are very small and varying across countries. In Spain, Article 54 from *Law 34/1998, on the hydrocarbons sector*, states that hydrogen is permitted only when it is injected with Synthetic Natural Gas (SNG) [102]. This constitutes a severe barrier. Largescale, flexible use of hydrogen in the gas grid would require harmonisation across EU Member states, and to allow higher concentrations it would be necessary to revise the overriding EU regulations [103].

5.5.2.8   Industry

According to a recent review, recent government policy on climate in Spain 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 [104]. 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 a "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 [105]. Here too hydrogen is regulated already, as an industrial chemical.

5.5.2.9 Drivers and barriers

Main drivers in the case of Moncayuelo are the EU policies to foster integration and motivate industrial-scale users to provide flexibility to the electricity system, as well as the draft NECP, which emphasizes ambitious goals for renewable energy production as well as specific targets for reduction of GHG emission in transport and industry.

Furthermore, the Region of Navarra has defined business development linked to renewable energy as a focus area under its smart specialization strategy. Important instruments are the *CEIN (European Business Innovation Centre)*, a service aiming to identify, promote and support SMEs and entrepreneurs, in order to consolidate and diversify the region's economic and industrial environment; *SODENA (Society for the Development of Navarra)*, a financial instrument that operates as a limited company and may take an active role in the different phases of business projects that contribute to the balanced and sustainable development of Navarra; and the *Moderna Plan*, which is the regional strategy, promoting change towards a knowledge-based economy, specialised in the areas of green economy, as well as health and talent economy [106]. These may also be conducive when it comes to hydrogen-wind systems.

On the other hand the regulation of hydrogen as an industrial chemical is associated with significant operational barriers, in that multiple authorities and permitting processes must be involved, and that electrolysers at smaller as well as larger scale are treated the same way as large, chemical industry complexes.

In Spain, as in Norway, it appears that incentives for industrial-scale provision of flexibility services are lacking, but there is an ongoing process to address these issues via the CNMC.

When it comes to deployment in transport, private as well as professional car users are incentivised through the MOVES program and there are specific targets for HRS roll-out. However, the lack of a Guarantee of Origin, as well as an accredited body for purity certification and standards for HRS are remaining barriers. Fuel cell trains and ships are not high on the agenda yet.

As regards gas grid injection, HyLAW highlighted the challenges associated with regulations based on calorific value and with thresholds that are varying across EU member states. Decarbonisation of industry is another area with great potential but a with fossil fuel lock-ins linked to existing infrastructure and process designs, implicating need for stronger incentives.

The main drivers and barriers, as well as certain key features of the legal-administrative frameworks for each element in the value chain, are summarized schematically in Table 44.

Table 44. Main drivers, barriers and central features of the legal-administrative framework for wind-H$_2$ integration in the Moncayuelo case.

Value chain components	Drivers	Neutral and conducive aspects	Barriers
Production & storage	Directive (EU) 2019/944, aiming to attract investment in energy storage and incentivise consumer contributions to stability Spain draft NECP: 20-21% reduction of GHG emissions and 74% share of renewables in electricity generation by 2030	Risk and safety requirements defined by the ATEX and SEVESO Directives IED Directive, regulating industrial emissions	Hydrogen production is considered as traditional chemical production facility Eight step permitting process involving several authorities EIA requirement
Distribution	National Action Framework for the development of the market and the infrastructures for alternative fuels in the transport sector	Harmonised: ADR European Agreement, Transportable Pressure Equipment Directive (TPED), implemented in national legislation ADR neutral, no particular barriers to FCEVs Tunnel and parking restrictions hardly applied IMO Interim recommendations for on-board transportation of hydrogen	Limited HRS availability Lack of a Guarantee of Origin High purity requirement, lack of accredited entity to verify quality No dedicated regulation or procedure for establishing an HRS
Use: flexibility services	Spain draft NECP: 74% share of renewables in electricity generation by 2030 Royal Decree 244/2019 regulates the administrative, technical and economic conditions for the self-consumption of electricity	Ongoing process to implement Directive (EU) 2019/944 and Regulation (EU) 2019/943,	Royal Decree 413/2014; fuel cells cannot be defined as renewable or cogeneration and are therefore not eligible for toll exemptions.
Use: gas grid injection	Need to decarbonize the gas grid	Gas Directive constitutes overarching framework	Lack of specific regulation, harmonised thresholds for hydrogen in the EU Hydrogen is permitted only in small amounts, when injected with SNG. This constitutes a severe barrier.

Value chain components	Drivers	Neutral and conducive aspects	Barriers
Use: transport	Draft NECP: reduce 43.5% of GHG emissions from transport by 2030 Funding program for efficient and sustainable mobility (MOVES Program) Regional and local policies for uptake of zero-emission cars Aim of 20 HRS and 500 FCEVs by 2020 National Action Framework for alternative fuels in the transport sector	Type approval and permits under common EU regulation Royal Decree 639/2016, establishes a framework for the implementation of infrastructure for alternative fuels New HRS must conform the quality characteristics of ISO 14687–2. Act 14/2014 of 24 July on Maritime Navigation, aims for uniformity between international conventions and domestic legislation	NECP not clear on what alternatives will be promoted for heavy-duty vehicles Lack a basic network of HRS Shipping hardly mentioned in the draft NECP Strong emphasis on battery-electric and biofuels in national policy
Use: industry	Draft NECP poses for the industry sector, in 2030, a reduction of CO_2 emissions of 74% over 2015 levels National tax on GHGs 'green cent' levy on the sale of fossil fuels, Recent government policy includes preparation of a roadmap to reduce GHG emissions in several industry sectors, as well developing a national Carbon Fund the NECP poses for the industry sector, in 2030, a reduction of CO_2 emissions of 74% over 2015 levels	Hydrogen is regulated already, as an industrial chemical	The Spanish industry sector has an extraordinarily important technological and economic challenge to advance in the path of decarbonization.

6 Conclusions and next steps

Three uses cases related to the H_2 production have been defined; 1) Raggovidda, 2) Smøela and 3) Moncayuelo. H_2 production costs have been calculated for several configurations and operation strategies for each use case.

Three scenarios have been defined to determine the possibility of operating the electrolyser under different operation strategies; 1) optimal H_2 production, 2) congestion management and 3) secondary frequency regulation service.

Additionally, socio-economic analyses of new hydrogen plants and potential effects of the job creation from the plants have been carried out, a regional I-O model called PANDA has been used for the Norwegian cases, and then generalised from the Norwegian results to the Spanish case. The socio-economic analyses included an assessment of regulations, codes and standards and the associated drivers and barriers to implementation in the three cases.

The obtained results show that the H_2 production costs differ a lot depending on the use case and on the operation strategy. In general, it is better to produce as much H_2 as possible as the electrolyser utilization factor for the analysed cases is quite low. In this sense, the combination of several operation strategies could significantly improve the utilization factor and reduce the production costs. In this respect it is important to highlight that the calculated LCOH2 is informative if there is a market for the produced H_2.

Summarising, the techno-economic analysis allows the following main conclusions:

- In case of the Wind-H_2-FC integrated system in Raggovidda it is not economically feasible to produce H_2 for re-electrification.
- In case of the Wind-H_2 integrated system in Smøla, regarding congestion management, considering the wind resources and the current remuneration scheme, it will not be economically feasible to increase the installed wind power over the power connection point export limit.
- In the case of Wind-H_2 integrated system in Moncayuelo, secondary frequency regulation as defined in Moncayuelo provides better results than the best optimal H_2 production use case with a minimal difference, since similar hydrogen sale prices are obtained with significantly less hours of operations.

The assessment of regulations, codes and standards highlights the role of legal-administrative frameworks and the interaction between processes at different levels. The key insights can be summarised as follows:

- The case at Raggovidda has national climate and energy policy as important drivers, as well as synergies with the strategies for ocean and regional development. However, there is a lack of incentives for flexibility services and industry deployment. There is a long-term potential, but also significant barriers associated with largescale deployment of hydrogen in the maritime, that must be addressed through international collaboration. To realise the potential associated with local industry and shipment of hydrogen or ammonia to Svalbard requires radical decisions and stronger measures at national level, alongside regional cooperation.

- The Smøla case is faced with similar challenges, but the potential for hydrogen deployment in the shorter term is to a larger extent influenced by regional and national authorities, given the economic geography and potential associated with green public procurement and public tendered ferries and passenger vessels in the area.
- In the case of Moncayuelo, a review of the legal-administrative context suggests a strong transition potential both in flexibility services, gas grad injection and road transport, and also in the longer term for industry and shipping. While the process to develop a market for flexibility services is ongoing, the development for gas grid injection depends on EU harmonisation. There is a stronger call for standardization and simplification of procedures than in Norway, possibly reflecting a more complex governance structure, less established hydrogen sector, and/or less focus on co-benefits and facilitation at local level.

Legal-administrative procedures exert considerable influence on the prospects for deployment and full-scale implementation of the HAEOLUS concept. The ongoing work to provide incentives and develop integrated markets for flexibility services is crucial. The lack of common EU legislation for gas grid injection of hydrogen is a serious barrier – harmonization may open up a huge market for green hydrogen. Intensified international collaboration is also necessary to address the regulatory gaps for maritime applications, which is a prioritized area in Norway. Development of hydrogen refuelling infrastructure is the most immediate challenge, to unleash the market for fuel cell electric vehicles. Operational barriers in the form of complex procedures and comprehensive assessment requirements are also found in many areas. Improved national coordination may alleviate these challenges. However, the main barriers, according to most stakeholders, are high costs and remaining uncertainties about the market. This implies that support to stimulate new solutions, as well as risk reduction measures, are of critical importance.

Regarding the socio-economic analysis based on the investments and operating cost a large amount of local jobs from building and operating the hydrogen plant is not expected. An effect of nine local jobs during the investment phase and four for the operating phase is expected. Considering that there are only 430 employees in Berlevåg, it is not an ignorable amount for this small community. Although the local job effects are expected to scale with the hydrogen output, there are differences in potential job effects for the three cases in local use of the hydrogen. In Berlevåg, hydrogen is relevant for aquaculture industry or as export to the island Svalbard, or alternatively as energy inputs for mining industry. In the Smøla case the hydrogen is expected to be demanded by lorries, rail, other maritime, cars, bus and high-speed ferries. For the Spanish case the municipalities such as Tafalla, Olite and Peralta have a more diversified industry structure that may benefit by the hydrogen production. In all cases the potential for new jobs from availability of hydrogen as energy input locally have not been quantified.

According to the obtained results and the progress of HAEOLUS project, next techno-economic analysis should be focused on the following aspects:

- Combination of electrolyser operation strategies related to congestion management (Scenario 3) and production at optimal H_2 production (Scenario 1).
- Include the H_2 demand profile and assess the impact on the H_2 production costs.

7 References

[1] Aaron Hoskin et al., 'IEA HYDROGEN IMPLEMENTING AGREEMENT –Task 24 "Wind Energy and Hydrogen Integration". 2007-2011. Final Report', Mar. 2013 [Online]. Available: http://ieahydrogen.org/pdfs/Task_24_final_report.aspx. [Accessed: 31-Mar-2020]

[2] 'Operation of the electricity system | Red Eléctrica de España'. [Online]. Available: https://www.ree.es/en/activities/operation-of-the-electricity-system. [Accessed: 12-Nov-2019]

[3] M. Santos and I. Marino, 'Haeolus Project Deliverable - D5.1: Energy analysis of the Raggovidda integrated system', 30-Jan-2019 [Online]. Available: http://www.haeolus.eu/wp-content/uploads/2019/01/D5.1.pdf. [Accessed: 07-Nov-2019]

[4] FCH 2 JU, 'Multi - Annual Work Program 2014 - 2020. FUEL CELLS AND HYDROGEN JOINT UNDERTAKING.' [Online]. Available: https://www.fch.europa.eu/sites/default/files/FCH%202%20JU%20MAWP-%20final%20%28ID%204221004%29.pdf. [Accessed: 14-Jan-2020]

[5] M. F. Shehzad, M. Bakr, D. Liuzza and L. Glielmo, ' Haeolus Project Deliverable – D6.1: Dynamic model for hydrogen production and storage plants', 11-Apr-2019, http://www.haeolus.eu

[6] M. F. Shehzad, M. B. Abdelghany, V. Mariani, D. Liuzza, L. Glielmo, 'Haeolus Project Deliverable – D6.3: Controlsystemformini-gridusecase', 04-Feb-2020, http://www.haeolus.eu

[7] I. Marino, M. Santos, 'Haeolus Project Deliverable – D8.1: Protocols for demonstration of energy-storage strategy', 17-Oct-2019, http://www.haeolus.eu

[8] E. Garcia, M. Santos, 'Haeolus Project Deliverable – D8.2: Protocols for demonstration of mini-grid strategy', 27-Feb-2020, http://www.haeolus.eu

[9] 'Haeolus Project Deliverable – D8.3: Protocols for demonstration of fuel-production strategy', Due to December 2020, http://www.haeolus.eu

[10] 'INGRID - High-capacity hydrogen-based green-energy storage solutions for grid balancing'. [Online]. Available: http://www.ingridproject.eu/. [Accessed: 14-Jan-2020]

[11] 'Forside - Varanger Kraft'. [Online]. Available: https://www.varanger-kraft.no/forside/. [Accessed: 26-Sep-2018]

[12] Statista. Global No.1 Business Data Platform, 'Norway - Inflation rate from 1984 to 2024', Statista. [Online]. Available: https://www.statista.com/statistics/327359/inflation-rate-in-norway/. [Accessed: 06-Apr-2020]

[13] eclareon GmbH, 'Norway', 17-Sep-2012. [Online]. Available: http://www.res-legal.eu/search-by-country/norway/. [Accessed: 20-Sep-2018]

[14] Olje- og energidepartementet, 'Meld. St. 25 (2015-2016)'. [Online]. Available: https://www.regjeringen.no/contentassets/31249efa2ca6425cab08130b35ebb997/no/pdfs/stm201520160025000dddpdfs.pdf. [Accessed: 05-Feb-2020]

[15] 'Smøla Wind Farm | Statkraft'. [Online]. Available: https://www.statkraft.com/energy-sources/Power-plants/Norway/Smola/. [Accessed: 05-Feb-2020]

[16] 'ACCIONA - Leading the world in renewable energies'. [Online]. Available: https://www.acciona-energia.com/. [Accessed: 11-Nov-2019]

[17] 'P.O.7.2. Resolución de 17 de diciembre de 2019, de la Comisión Nacional de los Mercados y la Competencia, BOE 313 Sec. III., pp.142951-142996'. 30-Dec-2019 [Online]. Available: https://www.ree.es/sites/default/files/01_ACTIVIDADES/Documentos/Procedimientos

Operacion/BOE-A-2019-18741_Comision_Nacional_Mercados_y_Competencia.pdf.
[Accessed: 28-Feb-2020]

[18] 'Welcome | ESIOS electricity · data · transparency'. [Online]. Available: https://www.esios.ree.es/en. [Accessed: 11-Nov-2019]

[19] IRENA (2019), Renewable power generation costs in 2018. International Renewable Energy Agency, Abu Dhabi [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf.

[20] Leontief, W.W. Quantitative input and output relations in the economic systems of the united states. Rev. Econ. Stat. 1936, 18, 105–125.

[21] Miller, R.E.; Blair, P.D. Input-Output Analysis: Foundations and Extensions; Cambridge University Press: Cambridge, UK, 2009

[22] Floristean, A., Brahy, N., Kraus, N. (2018). List of Legal Barriers. Deliverable 4.2. HyLAW project (FCH JU). URL: https://www.hylaw.eu/sites/default/files/2019-01/D4.2%20-%20List%20of%20legal%20barriers.pdf

[23] Damman, S., Sandberg, E., Rosenberg, E., Pisciella, P., Johansen, U. (2020). Largescale hydrogen production in Norway - possible transition pathways towards 2050. SINTEF report no. 2020-00179. URL: https://www.sintef.no/publikasjoner/publikasjon/?pubid=CRIStin+1794574

[24] E. Riise, E. Holmelin, G. Klavenes (2010). Regionale og lokale ringvirkninger av vindkraftutbygging, 2010, Report (Norwegian)

[25] E. Riise, E. Holmelin, G. Klavenes (2016). Samfunnsmessige virkninger av vindkraftverk - En etterprøving av fire vindkraftverk, 2016, Report (Norwegian)

[26] European Commission (2014). 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]. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0034

[27] European Commission (2012). SEVESO Directive [Directive 2012/18/EU, on the control of major-accident hazards involving dangerous substances] URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012L0018

[28] Norwegian Government (2009). Regulation on handling of inflammable, reactive and pressurised substances and equipment and facilities used in the handling of such substances [FOR-2009-06-08-602] Norway. URL: https://lovdata.no/dokument/SF/forskrift/2009-06-08-602

[29] Norwegian Government (2015). El-safety Act. [Lov om tilsyn med elektriske anlegg og elektrisk utstyr (el-tilsynsloven)], last amended 2015. URL: https://lovdata.no/dokument/NL/lov/1929-05-24-4

[30] Norwegian Government (2016). Regulation on electrical low voltage installations [Forskrift om elektriske lavspenningsanlegg] last amended 01.06.2016. Norway. URL: https://lovdata.no/dokument/SF/forskrift/1998-11-06-1060

[31] Norwegian Government (2017). Regulation of equipment and safety systems for use in explosive atmospheres. [Forskrift om utstyr og sikkerhetssystem til bruk i eksplosjonsfarlig område (FUSEX)] FOR-2017-11-29-1849, Norway. URL: https://lovdata.no/dokument/SF/forskrift/2017-11-29-1849

[32] Norwegian Government (2016). Regulation on Control of Major Accident Hazards Involving Dangerous Substances [Forskrift om tiltak for å forebygge og begrense konsekvensene av storulykker i virksomheter der farlige kjemikalier forekommer (storulykkeforskriften)] Norway. URL: https://lovdata.no/dokument/SF/forskrift/2016-06-03-569

[33] Norwegian Directorate for Civil Protection (2016). Guideline for obtaining Special Consent [Temaveiledning om innhenting av samtykke. URL: https://www.dsb.no/lover/farlige-stoffer/veiledning-til-forskrift/temaveiledning-om-innhenting-av-samtykke/

[34] Hambro, E. (2015). Natur og klima – kan vi sikre begge deler? Presentation by the Norwegian Environment Agency, 17th April 2015. https://naturvernforbundet.no/getfile.php/1382411-1429876296/Bilder/Energi/Fornybar%20energi/1%20SRN-seminar%202015%20Ellen%20Hambro.pdf

[35] Norwegian Government (2016). White paper on energy (Meld. St. 25 (2015–2016)), Norway. URL: https://www.regjeringen.no/no/dokumenter/meld.-st.-25-20152016/id2482952/

[36] Norwegian Government (2019). Regulation on grid regulation and electricity market (NEM) [Forskrift om nettregulering og energimarkedet (NEM)] FOR-2019-10-24-1413, Norway. URL: https://lovdata.no/dokument/SF/forskrift/2019-10-24-1413

[37] Norwegian Ministry for Petroleum and Energy (2019). Memo for public hearing on the proposed NEM regulation. URL: https://www.regjeringen.no/contentassets/6ea2b5407c3142a7ac8c221dee7247a2/horingsnotat-1-l975313.pdf

[38] Norwegian Directorate for Civil Protection (2016). Guideline for storage of dangerous substances [Temaveiledning for oppbevaring av farlig stoff], Directorate for Civil Protection, Norway, 2016. URL: https://www.dsb.no/globalassets/dokumenter/farlige-stoffer-npf/industrisikkerhet/temaveiledning-om-oppbevaring-av-farlig-stoff.pdf

[39] Norwegian Government (2017). Regulation of Pressure Equipment (Forskift om trykkpåkjent utstyr,), of 11th October 2017, Norway. URL: https://lovdata.no/dokument/SF/forskrift/2017-10-10-1631?q=trykkp%C3%A5kjent%20utstyr

[40] NFPA (2020). Hydrogen Technologies Code. URL: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=2

[41] Norwegian Government (2009). Regulation of land transport of dangerous goods [Forskrift om landtransport av farlig gods], FOR-2009-04-01-384, Norway. URL: https://lovdata.no/dokument/SF/forskrift/2009-04-01-384

[42] Norwegian Government (2012). Regulation on transportable pressure equipment [Forskrift om transportabelt trykkutstyr], FOR-2012-11-22-1088, Norway. URL: https://lovdata.no/dokument/SF/forskrift/2012-11-22-1088

[43] International Maritime Organisation (2016). International Maritime Dangerous Goods (IMDG) Code. URL: http://www.imdgsupport.com/free%20imdg%20code%20introduction%2037-14.pdf

[44] International Maritime Organisation (1986). (International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC) Code (IMO MSC 5(48)), International Maritime Organization. URL: https://www.mardep.gov.hk/en/msnote/pdf/msin1547anx1.pdf

[45] International Maritime Organisation (2016). Interim recommendations for carriage of liquefied hydrogen in bulk (MSC.420(97). URL: http://www.imo.org/en/KnowledgeCentre/

IndexofIMOResolutions/Maritime-Safety-Committee-%28MSC%29/Documents/MSC.420%2897%29.pdf

[46] Norwegian Government (1987). 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, URL: University of Oslo: https://app.uio.no/ub/ujur/oversatte-lover/data/for-19870521-0406-eng.pdf

[47] Norwegian Directorate for Civil Protection (2011). Guideline for tapping of dangerous substances [Temaveiledning om omtapping av farlig stoff] Directorate for Civil Protection, 2011, Norway. URL: https://www.dsb.no/lover/farlige-stoffer/veiledning-til-forskrift/temaveiledning-om-omtapping-av-farlig-stoff

[48] Norwegian Government (2019). The Government's Action Plan for Green Shipping (2019) [Handlingsplan for grønn skipsfart], issued 20. June 2019. URL: https://www.regjeringen.no/contentassets/2ccd2f4e14d44bc88c93ac4effe78b2f/the-governments-action-plan-for-green-shipping.pdf

[49] Norwegian Directorate for Civil Protection (2016). Guideline on safety for enterprises falling under the major hazard prevention regulation [Temaveiledning til storulykkeforskriften § 7 om strategi for å forebygge og begrense storulykker]. URL: https://www.dsb.no/globalassets/dokumenter/farlige-stoffer-npf/industrisikkerhet/temaveiledning-om-innhenting-av-samtykke.pdf

[50] Madslien, A., Hulleberg, N., Kwong, C.K. (2019). Framtidens transporter. Framskrivinger for person- og godstransport 2018-2050. [Transport projections for Norway, 2018-2050]. TØI rapport 1718.2019. URL: https://www.toi.no/getfile.php?mmfileid=51596

[51] Norwegian Government (2017). Climate Act (LOV-2017-06-16-60), Norway [Lov om klimamål, 2017]. URL: https://lovdata.no/dokument/NL/lov/2017-06-16-60

[52] National Action plan for infrastructure for alternative fuels in transport [Handlingsplan for infrastruktur for alternative drivstoff i transport], 1. July 2019, Norwegian Government. URL: https://www.regjeringen.no/contentassets/67c3cd4b5256447984c17073b3988dc3/handlingsplan-for-infrastruktur-for-alternative-drivstoff.pdf

[53] Floristean A, Brahy NK, Skiker S, Damman S, Hayter D, Nozharova D (2019). EU Policy Paper. Deliverable 4.5, HyLAW project. https://www.hylaw.eu/sites/default/files/2019-03/EU%20Policy%20Paper%20%28March%202019%29.pdf

[54] Norwegian Government (2017). Regulation on Public Procurement (Forskrift om offentlige anskaffelser (anskaffelsesforskriften), in force from 01.01.2017, Norway. URL: https://lovdata.no/dokument/SF/forskrift/2016-08-12-974?q=forskrift om offentlige anskaffelser

[55] CertifHY (2016). Technical Report on the Definition of 'CertifHy Green' Hydrogen', Deliverable No. D2.4, 22. August 2016. URL: https://www.fch.europa.eu/sites/default/files/project_results_and_deliverables/D2.4.%20green%20hydrogen%20definition_update_final.pdf. Last visited 02.06.2019

[56] European Commission (2014). Directive 2014/94/EU, on the deployment of alternative fuels infrastructure [the AFID Directive]. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=EN

[57] Norwegian Government (2008). Planning and Building Act [Lov om planlegging og byggesaksbehandling (plan- og bygningsloven)], LOV-2008-06-27-71, Norway. URL: https://lovdata.no/dokument/NL/lov/2008-06-27-71?q=Plan og bygningsloven

[58] Norwegian Government (2002). Fire Prevention Act [Lov om vern mot brann, eksplosjon og ulykker med farlig stoff og om brannvesenets redningsoppgaver (brann- og eksplosjonsvernloven)] LOV-2002-06-14-20, Norway. URL: https://lovdata.no/dokument/NL/lov/2002-06-14-20?q=brannvernloven

[59] Norwegian Government (2015). New emission commitment for Norway for 2030 – towards joint fulfilment with the EU (Meld. St. 13 (2014-2015)), white paper, Norwegian Ministry for Climate and Environment. URL:https://www.regjeringen.no/no/dokumenter/meld.-st.-13-2014-2015/id2394579/?ch=1

[60] Norwegian Government (2017). Public Procurement Act [Lov om offentlige anskaffelser, LOV-1999-07-16-69] in force from 01.01 2017. URL: https://lovdata.no/dokument/NL/lov/2016-06-17-73?q=anskaffelsesloven

[61] Norwegian Government (2019). The Government's updated ocean strategy. [Blå muligheter. Regjeringens oppdaterte havstrategi]. https://www.regjeringen.no/globalassets/departementene/nfd/dokumenter/strategier/nfd_havstrategi_2019_norsk_uu.pdf

[62] Norwegian Directorate for Civil Protection (2015). Use of dangerous substances - part I - Facilities for use of liquid and gaseous fuels. Guideline. URL: https://www.dsb.no/lover/farlige-stoffer/veiledning-til-forskrift/temaveiledning-om-bruk-av-farlig-stoff-del-1---forbruksanlegg-for-flytende-og-gassformig-brensel/

[63] Norwegian Government (2004). Regulation to restrict pollution [Forskrift om begrensning av forurensning (forurensningsforskriften)], last amended 2016, Norway. https://lovdata.no/dokument/SF/forskrift/2004-06-01-931

[64] Enova (2017). Norsk industri mot lavutslippssamfunnet [Norwegian industry towards a low-emission society] Report, November 2017. Downloadable from www.enova.no

[65] Karakaya E, Nuur C, Assbring L (2018). Potential transitions in the iron and steel industry in Sweden: Towards a hydrogen-based future? Journal of Cleaner Production 195: 651-663. DOI: https://doi.org/10.1016/j.jclepro.2018.05.142

[66] THEMA (2018). Alternativer for framtidig energiforsyning på Svalbard [Alternatives for future energy supply at Svalbard. Report to the Norwegian Ministry for Petroleum and Energy. URL:https://www.regjeringen.no/contentassets/cdaceb5f6b5e4fb1aa4e5e151a87859a/thema-og-multiconsult---energiforsyningen-pa-svalbard.pdf

[67] Statkraft (2018). Fornybar energiforsyning til Svalbard – Longyearbyen. Innspillsnotat, 9 november 2018. URL: https://www.statkraft.com/globalassets/explained/svalbard_rapport_0911_final.pdf

[68] NRK (2020). Norwegian Government raising its climate targets – to cut at least 50%. News report, 07.02.2020. URL: https://www.nrk.no/norge/regjeringen-skrur-opp-klimamalene_-skal-kutte-minst-50-prosent-1.14893477

[69] Norwegian Directorate for water resources and energy (2019). Norge og Sverige har oppnådd det felles målet i elsertifikatordningen om 28,4 TWh ny fornybar kraftproduksjon innen 2020. Press release, 28.05.2019. https://www.nve.no/nytt-fra-nve/nyheter-energi/28-4-twh-ny-kraftproduksjon-siden-2012/

[70] DNV GL (2019). Synteserapport om produksjon og bruk av hydrogen i Norge, rapportnr. 2019-0039, Rev 1. URL: https://www.regjeringen.no/contentassets/0762c0682ad04e6abd66a9555e7468df/hydrogen-inorge---synteserapport.pdf

[71] Schäffer, L.S., Rosenberg, E., Pisciella, P., Damman, S., Espegren, K.A., Fodstad, M., Graabak, I., Perez-Valdes, G., Sandberg, E., Johansen, U., Seljom, P.M.S., Tomasgard, A. (2020). Veikart for energi i Norge mot 2050. SINTEF Rapport 2019:01467 URL: https://www.sintef.no/publikasjoner/publikasjon/?pubid=CRIStin+1793057

[72] NVES (2018). Hydrogentog Raumabanen. Report from Norsk Vindenergisenter AS, 30.10.2018. URL: https://nves.no/site/wp-content/uploads/2019/07/Hydrogen-Raumabanen-v1.1.pdf

[73] NVES (2018). Vindkraft til hydrogen – nye muligheter for Smøla. URL: https://nves.no/site/wp-content/uploads/2019/07/Hydrogenrapport-v.2.1-vindkraft-til-hydrogen.pdf

[74] 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, Norway. URL: https://www.dsb.no/globalassets/dokumenter/farlige-stoffer-npf/industrisikkerhet/temaveiledning_transport_distribusjon_petroleum_roerledning_over_land.pdf

[75] Norwegian Maritime Authority (2016). Regulations on ships using fuel with a flashpoint of less than 60°C and other regulatory amendments – implementation of the IGF Code. Circular RSR-18-2016. URL: https://www.sdir.no/contentassets/08693ff060624261a6320ab603e53c6e/eng-rsr-18-2016.pdf?t=1582275211987

[76] International Maritime Organisation (2013). MSC.1/Circ.1455 – guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments. URL: https://www.mardep.gov.hk/en/msnote/pdf/msin1339anx1.pdf

[77] Hydrogen Region Vestlandet (2019). Strategi og handlingsprogram 2019-2020. Strategy document published by Vestlandsrådet, 28.01.2019. URL: http://www.vestlandsraadet.no/downloadFiletransferSessionFile?filetransferSessionId=1&filetransferId=10003771

[78] ADR/RID 2019 – Regulation 1. April 2009, no. 384 on road transportation of dangerous goods [Forskrift 1. April 2009, nr. 384 om landtransport av farlig gods] URL: https://www.dsb.no/lover/farlige-stoffer/artikler/adrrid/

[79] FCH JU (2019) Study on the use of fuel cells & hydrogen in the railway environment. Report 3. URL: https://shift2rail.org/wp-content/uploads/2019/04/Report-3.pdf

[80] Directorate for railways, Norway (2019). NULLFIB. Sluttrapport. URL: https://www.jernbanedirektoratet.no/contentassets/8a4e22f34a3147d8b7c94e2843abfd3d/sluttrapport-nullfib.pdf

[81] Norwegian Government (2015). Maritime strategy. [Maritime muligheter – blå vekst for grønn fremtid. Regjeringens maritime strategi]. URL: https://www.regjeringen.no/contentassets/05c0e04689cf4fc895398bf8814ab04c/maritim-strategi_web290515.pdf

[82] Floristean, A., Mougin, J., Hayter, D., Nozharova, D. (2018). HyLAW. Cross-country Comparison. Deliverable D4.4. https://www.hylaw.eu/sites/default/files/2018-11/D.4.1%20-%20Analysis%20of%20commonalities%20and%20differences%20between%20countries.pdf

[83] Gómez-Acebo & Pombo Abogados (2013). Recent amendments and reforms to the energy sector: Law 15/2012 and Royal Decree Law 29/2012. https://www.lexology.com/library/detail.aspx?g=2d3eafa2-a7ba-4a54-a3f9-24bf5bae2177

[84] Olivera, G., Artés, A. (2019). Electricity Regulation. Spain. https://gettingthedealthrough.com/area/12/jurisdiction/21/electricity-regulation-2020-spain/

[85] Spanish Government (2017). Royal Decree 656/2017 – Regulation of Storage of Chemical Products and its Complementary Technical Instructions MIE APQ 0 to 10. URL: https://www.boe.es/eli/es/rd/2017/06/23/656

[86] European Commission (2008). 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

[87] UNECE (2017). 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

[88] European Commission (2010). Transportable Pressure Equipment Directive (TPED) (Directive 2010/35/EU). https://eur-lex.europa.eu/eli/dir/2010/35/oj

[89] Spanish Government (2014). Act 14/2014 of 24 July on Maritime Navigation (the Maritime navigation Law or MNL). URL: 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

[90] LIFE Plan-Up (2019). Fit to succeed? An assessment of the Spanish draft energy and climate plan. May 2019. URL: https://cdn.webdoos.io/planup/d83f03617bdc165ac88fd7b807e7c1b1.pdf

[91] Agencia Insular de Energía de Tenerife (2019). Approved the MOVES plan for the purchase of electric cars, 21 February 2019. URL: https://www.agenergia.org/en/approved-the-moves-plan-for-the-purchase-of-electric-cars/ .

[92] Wappelhorst, S. (2019). "Spain's booming hybrid electric vehicle market: A summary of supporting policy measures," ICCT WORKING PAPER 2019-12, 2019.

[93] Spanish Government (2016). Royal Decree 639/2016 of 9 December 2016 on the deployment of alternative fuels infrastructure. URL: https://www.boe.es/diario_boe/txt.php?id=BOE-A-2017-8755

[94] HyLAW (2018). Informe de Recomendaciones Legislativas para el Sector del Hidrógeno en España. https://www.hylaw.eu/sites/default/files/2019-02/HyLAW_%20National%20policy%20Paper_SPA_Final.pdf)

[95] Spanish Government (2016). National Action Framework for Alternative Energy in Transport. URL: https://industria.gob.es/es-ES/Servicios/Documents/national-action-framework.pdf

[96] European Commission (2017). Summary on national plans for alternative fuel infrastructure. URL: https://ec.europa.eu/transport/sites/transport/files/2017-11-08-mobility-package-two/summary_of_national_policy_frameworks_on_alternative_fuels.pdf

[97] International Maritime Organization (2015). Resolution MSC.391(95) (adopted on 11 June 2015) Adoption of the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code). URL: http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Maritime-Safety-Committee-(MSC)/Documents/MSC.391(95).pdf

[98] European Commission (2014). Directive 2014/90/EU on marine equipment. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0090&from=EN

[99] European Commision (2009). Directive 2009/45 on safety rules and standards for passenger ships (recast). URL: https://eur-lex.europa.eu/LexUriServ/ LexUriServ.do?uri=OJ:L:2009:163:0001:0140:EN:PDF

[100] Osborne Clarke (2019). Analysis of the key developments introduced by the new Royal Decree 244/2019, of 5th April, regulating the administrative, technical and economic conditions of self-consumption of electrical energy. 11th April 2019. https://www.osborneclarke.com/insights/analysis-key-developments-introduced-new-royal-decree-2442019-5th-april-regulating-administrative-technical-economic-conditions-self-consumption-electrical-energy/

[101] European Commission (2009). The Gas Directive [Directive 2009/73/EC, concerning common rules for theinternal market in natural gas]. URL: https://eur-lex.europa.eu/legal-content/ EN/TXT/?uri=CELEX:02009L0073-20190523

[102] Spanish Government (1998). Law 34/1998, on the hydrocarbons sector. URL: https://www.boe.es/buscar/act.php?id=BOE-A-1998-23284

[103] Hayter, D. (2018). HyLAW Horizontal Position Paper - Gas Grid Issues. URL: https://www.hylaw.eu/sites/default/files/2019-02/HyLAW_Horizontal%20Position%20Paper_Gas%20Grid%20Issues.pdf

[104] De Miguel Perales, C. and J. A. Sedano Lorenzo (2019). Climate Regulation: Spain. Getting the deal through, 2019. URL: https://gettingthedealthrough.com/area/42/jurisdiction/21/ climate-regulation-2020-spain/

[105] Almenar, J., Alcaraz, C. and O. Canseco (2019). Environmental law and practice in Spain: overview. Thomson Reuters Practical Law, 2019. URL: https://uk.practicallaw.thomsonreuters.com/0-521-6274?transitionType=Default&contextData=(sc.Default)&firstPage=true&bhcp=1

[106] European Commission (2020). EU Regional Innovation Monitor Plus: Chartered Community of Navarre. URL: https://ec.europa.eu/growth/tools-databases/regional-innovation-monitor/base-profile/chartered-community-navarre-archived (Accessed January, 10th, 2020).