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Energy analysis of the Raggovidda integrated system

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Abstract:	Techno economic analysis of the operation of a 2.5 PEM electrolyser installed in the 45 MW Raggovidda wind farm. Two scenarios are presented, the first covers the operation of the electrolyser according to sport market electricity prices and the second is related to electricity grid congestions management.

Revision History

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Acronyms and glossary of terms

CAPEX: Capital expenditures

EU: European Union

H_2: Hydrogen

LCOE: Levelized cost of Energy

LCOS: Levelized cost of storage

LCOH2: Levelized cost of hydrogen

M€: Million (10^6) euros

Nm^3: Normal cubic meter

NPV: Net present value

OPEX: Operational expenditures

PEM: Proton Exchange Membrane

PV: Present value

RES: Renewable energy system

1 Introduction

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

The Raggovidda wind farm is located in a remote area of Norway, the Varanger peninsula. The wind farm is situated at an elevation of approximately 400 m above sea level and 30 km south of the town of Berlevåg. Raggovidda has a granted concession of 200 MW, but only 45 MW of capacity have been built due to limitations in the grid export capacity. Steady winds result in high capacity factors of about 50 %. Raggovidda wind farm is owned by Varanger Kraft and produced just short of 200 GWh in 2015 [1].

HAEOLUS project impact is expected to be relevant for the following aspects:

- The wind farm is in a sub-grid with limited export capacity (95 MW at Varanger) compared to its full concession of 200 MW;
- Storing excess energy as hydrogen will help reduce uncertainty in wind power production, which is much larger than total consumption in the Varanger peninsula: relatively small uncertainties can destabilise the grid;
- In the long term, Varanger Kraft are strategically interested in exploiting their full wind power potential by producing and exporting hydrogen in large scale.

This report summarises the results of the techno-economic analysis carried out for analysing the integration and operations of the electrolyser in the wind farm under different operational scenarios. These results are the basis for the detailed control system design (WP6) and business model development (WP3).

1.1 Structure of the document

This report is organized in six sections:

- Introduction: brief introduction to the HAOELUS project and the Raggovidda wind farm where a 2.5 MW electrolyser will be installed and operated
- Techno-economic analysis of wind-hydrogen systems: description of the methodology and main calculations used for the techno-economic analysis. Two operation scenarios are presented.
- Input data: description of the characteristics and main data necessary for the analysis of the wind hydrogen system. This includes data of the electricity market in Norway, wind farm
- Scenario 1 - Optimal H_2 production: techno-economic analysis of the operation of a 2.5 MW electrolyser in the Raggovidda wind farm to produce H_2 at the lowest possible cost.
- Scenario 2 - Production congestion management: techno-economic analysis of the operation of an electrolyser to take advantage of the wind energy that otherwise would be waster due to production restriction in the connection point.
- Conclusions.

2 Techno-economic analysis of wind-hydrogen systems

2.1 Methodology

The main objective of the study is to analyse from a techno-economical perspective the optimal sizing and coordinated operation of Raggovidda wind hydrogen (wind-H_2) system under different working scenarios. The so-called wind-H_2 systems will be constituted by current 45 MW Raggovidda wind farm and 2.5 MW electrolyser, nevertheless the studies will not be limited to these sizes.

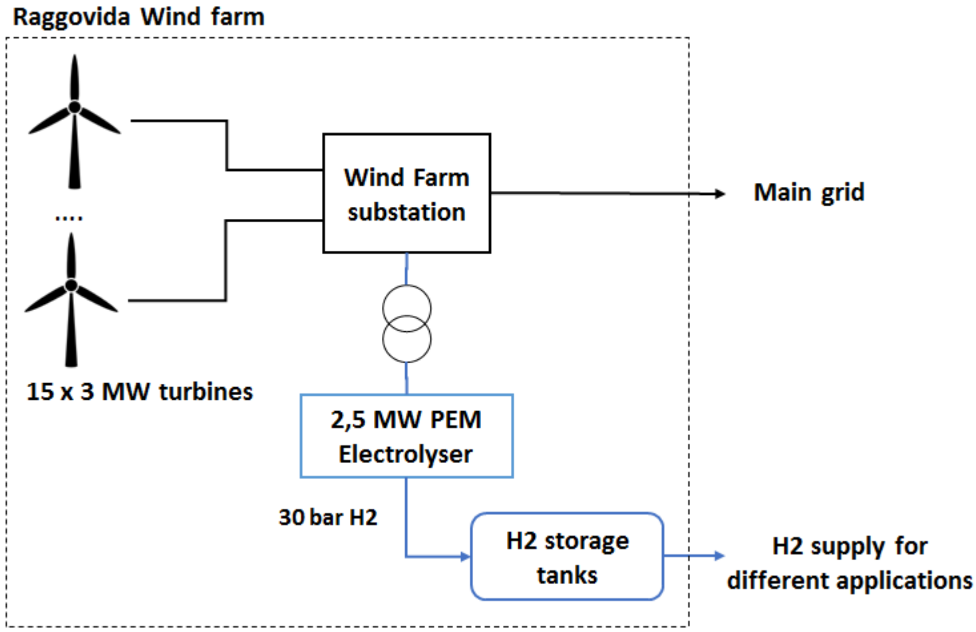

Figure 1. Conceptual layout of the Raggovidda wind-H_2 system

The electrolyser will generate H_2 according to a certain operation strategy, and this H_2 will be subsequently used in other applications out of the fence of the wind farm, as for example powering fishing boats, transportation or industrial processes among others. The use and exploitation of the H_2 produced in Raggovidda is currently under analysis in WP3 of this project. Currently, as there has not yet been established a specific use and a reference price for the H_2, these studies have not considered any income from the sale of the produced H_2.

The HAEOLUS project includes a 120 kW PEM fuel cell that will be used to re-electrify the produced H_2 while other local markets for H_2 are developed. However, the fuel cell is not a key element for the future Raggovidda wind-H_2 systems, in consequence it has not been taken into consideration in the scenario analysis.

Two operational scenarios will be analysed.

1. **Optimization of H_2 production cost based on spot market electricity prices**: operation of the electrolyser based on the spot market energy prices, producing H_2 when the price is below a certain threshold.
2. **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.

These studies have been carried out by means of a TECNALIA's proprietary tool for energy storage systems design, that has been adapted with an 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 within the wind farm under the above-mentioned scenarios. The tool also permits to carry out sensitivity analysis to assess the effect of certain parameters on the overall system performance. The results are presented through a graphical user interface and are exported to an excel file. Figure 2 shows the main graphical user interface of the tool:

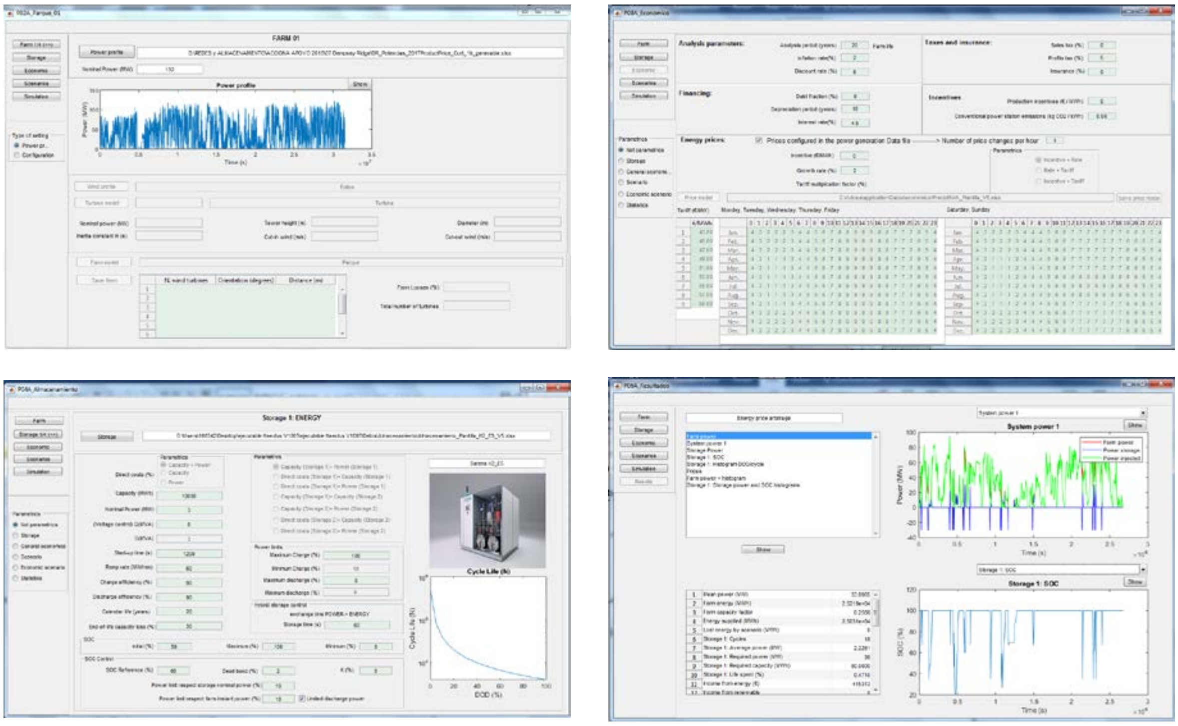

Figure 2. Main configuration and results screen of the Hydrogen and energy storage techno-economic analysis tool

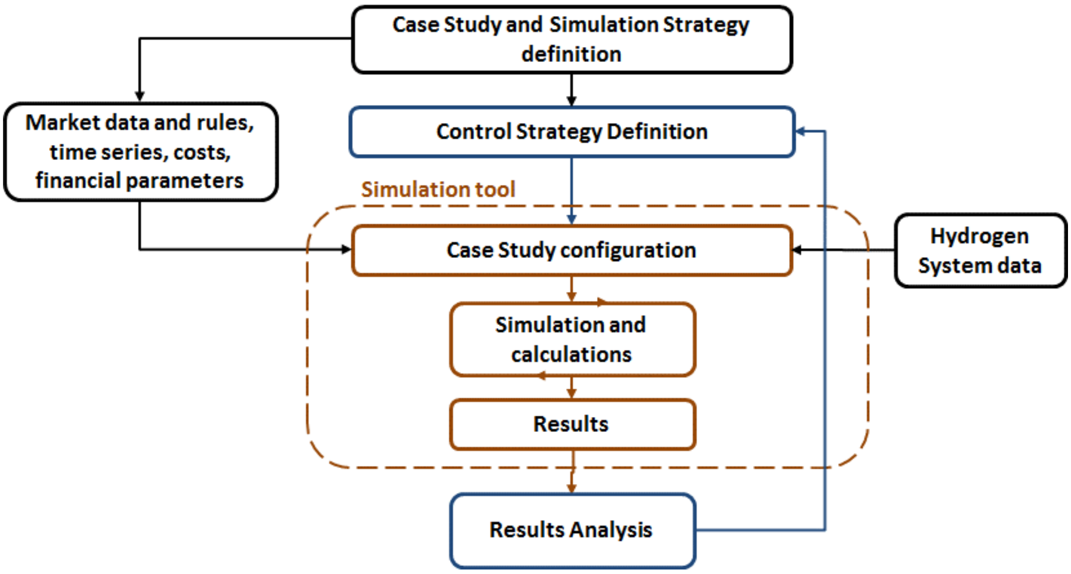

Figure 3. Techno-economic studies overall methodology

The methodology followed for the three scenarios techno-economic analysis consist of 4 major steps as it can be seen in Figure 3.

1. **Case study and simulation strategy definition.** The first step is basically related to the selection of the input data and the definition of the simulation strategy, which means defining which are the most relevant results to be calculated and optimized and selecting the sensitivity parameters to be studied. For this study the input data is basically constituted by:
   a. Wind farm generation data series
   b. Spot market energy price data series
   c. Specific data related to the cases studies:
      i. Wind farm power connections point power restrictions
      ii. Frequency regulation requirement and price data series
2. **Hydrogen system data.** Definition of the techno-economic parameters of the H_2 system, which is basically the data of the PEM electrolyser manufactured by Hydrogenics. Although a 2.5 MW electrolyser will be integrated in the Raggovidda wind farm, from a theoretical perspective other electrolyser sizes will be also considered.
3. **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.
4. **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.
5. **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.

2.2 Main calculations

The techno-economic analysis basically pursues the optimization of the economic performance of wind-H_2 system under different working conditions. Usually, the main economic parameter to evaluate and optimize is the net present value (NPV) of the system or investment for a given period.

$$NPV = \sum_{i=0}^{n}\left[\text{Income}_i \cdot \left(\frac{1+e}{1+d}\right)^i - \text{CAPEX}_i \cdot \left(\frac{1}{1+d}\right)^i - \text{OPEX}_i \cdot \left(\frac{1+e}{1+d}\right)^i\right] +$$

$$+\text{Remaining Value}_n \cdot \left(\frac{1}{1+d}\right)^n$$

Equation 1

Where

- **n**: analysis period, in this study it has been fixed to 20 years, which is the typical analysis period for a wind farm.
- **i:** years.
- **e**: inflation rate.
- **d**: discount rate.

- **Income:** is the sum of all the income sources of the wind H_2 system. Depending on the scenarios they could be the followings:
    - Sale of energy: this is the only current source of revenue of the Raggovidda wind farm. The price per MWh fed to the grid is calculated according to remuneration scheme described in 4.1.3.
    - Sale of H_2: it has not been considered any income from sales of H_2, but the production cost was calculated.
- **CAPEX:** capital expenditures are constituted by the wind farm and electrolyser investment costs.
- **OPEX:** operation and maintenance costs of both wind farm and electrolyser.
- **Remaining value:** this parameter refers to 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.

As it has been previously mentioned, no income for the sale of H_2 has been considered, as consequence the NPV of wind farm with an electrolyser is always worse than the base case scenario without electrolyser. Considering this, the NPV or other economic parameters as Investment Payback or Investment Rate of Return (IRR) are not the most representative ones for evaluating such a system. Thus, in this 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 version of the Levelized Cost of Energy (LCOE), which is 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:

$$\mathrm{LCOE}\left(\frac{€}{\mathrm{kWh}}\right)=\frac{\sum_{i=0}^{n}\left[\mathrm{CAPEX}_i\cdot\left(\frac{1}{1+d}\right)^i+\mathrm{OPEX}_i\cdot\left(\frac{1+e}{1+d}\right)^i\right]}{\sum_{i=1}^{n}\mathrm{Energy\ production}_i\cdot\left(\frac{1+e}{1+d}\right)^i} \qquad \text{Equation 2}$$

Where

- **n**: analysis period, in this study it has been fixed to 20 years, which is the typical analysis period for a wind farm.
- **i:** years.
- **e**: inflation rate.
- **d**: discount rate.
- **CAPEX_i:** wind farm annual capital costs, including debt cost.
- **OPEX_i:** wind farm annual operation and maintenance costs.
- **$\mathrm{Energy\ production}_i$:** wind farm annual energy fed to the grid.

The LCOH2 can be calculated as the H_2 sale price that makes the NPV of the wind-hydrogen system equal to the NPV of the base case.

$$\mathrm{LCOH2}\left(\frac{€}{\mathrm{kg}}\right)=\frac{\mathrm{NPV}_{\mathrm{Base\ Case}}-\mathrm{NPV}_{\mathrm{wind+H_2}}}{\sum_{i=1}^{n}\mathrm{H_2\ production}_i\cdot\left(\frac{1+e}{1+d}\right)^i} \qquad \text{Equation 3}$$

Where

- **$NPV_{BASE\ CASSE}$:** Net present value of the base case scenario, which is a wind farm without electrolyser.
- **$NPV_{wind+H2}$:** Net present value of the wind farm with electrolyser.

The LCOH2 can be also calculated in some cases through the traditional LCOS formula adapted to the case of H_2:

$$\mathrm{LCOH2}\left(\frac{€}{\mathrm{kg}}\right)=\frac{\sum_{i=0}^{n}\left[\mathrm{CAPEX}_i\cdot\left(\frac{1}{1+d}\right)^i+\mathrm{OPEX}_i\cdot\left(\frac{1+e}{1+d}\right)^i+\mathrm{Energy\ Cost}_i\cdot\left(\frac{1+e}{1+d}\right)^i\right]}{\sum_{i=1}^{n}\mathrm{H_2\ production}_i\cdot\left(\frac{1+e}{1+d}\right)^i}$$

Equation 4

Where:

- **$CAPEX_i$:** electrolyser annual capital costs, including debt cost.
- **$OPEX_i$:** electrolyser annual operation and maintenance costs.
- **H_2 $production_i$:** is the amount of the produced H_2 per year.
- **Energy $Cost_i$:** is the cost of the energy consumed for producing H_2. In practice, as the electrolyser will be installed inside the wind farm, it is not a direct cost but a loss of income as the energy consumed for H_2 productions is not fed to the grid.

Depending on the case study, Equation 3 and Equation 4 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, in this case Equation 3 must be used.

3 Input data identification and definition

This section summarises the most relevant data of the wind farm, electrolyser and electric market necessary for the techno-economic analysis of three described scenarios.

3.1 Raggovidda Wind Farm

3.1.1 Main characteristics and costs

Table 1 summarised the general information of the Raggovidda wind farm provided by Varanger Kraft [2].

Table 1. General information of the Wind Farm

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

Wind farm CAPEX and OPEX reference values are not directly those of Raggovidda wind farm, but they have been estimated according to current state of the art and market data provided by Varanger Kraft.

CAPEX has been defined as the costs per installed kW, including all the incurred costs as civil works, turbine cost, deployment, electrical connection, engineering and permissions among others.

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

3.1.2 Wind farm production

Table 2 summarised the results from the statistical study of the real generation of the Raggovidda 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 only a slight variation (<8%) in the annual generation from one year to another. Regarding the hourly generation profile, the histogram in Figure 4 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-year data have been selected as the reference for the techno-economic studies.

Table 2.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

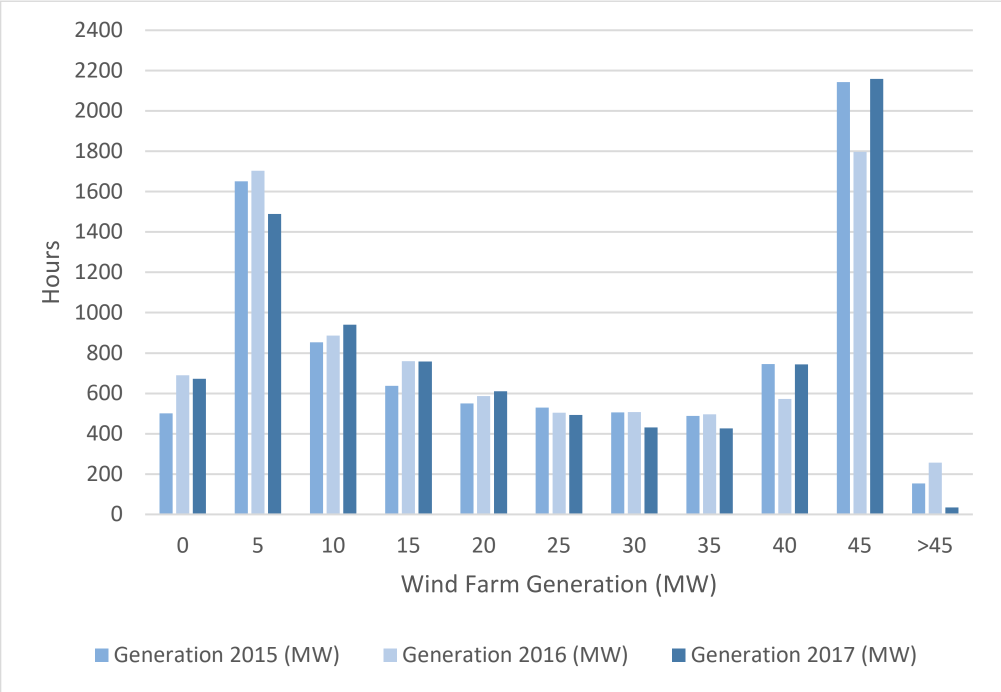

Figure 4. Histogram of Raggovidda Wind farm generation 2015-2017

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.

$$\text{Electricity price} = \text{Spot market price} + \text{Green certificate} + \text{Guarantee} - \text{Tariffs} \qquad \text{Equation 5}$$

This section described the remuneration scheme and the values that have been used for the simulations.

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

Table 3 summarised the statistical data of the electricity spot market of the POC of Raggovidda Wind Farm (Tromsø) for 2015, 2016 and 2017 years. For each year maximum, minimum, mean prices are shown. As it can be seen there is a variation from one year to another regarding maximum and minimum values, whereas mean prices are quite similar. Figure 5 histogram 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 3.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

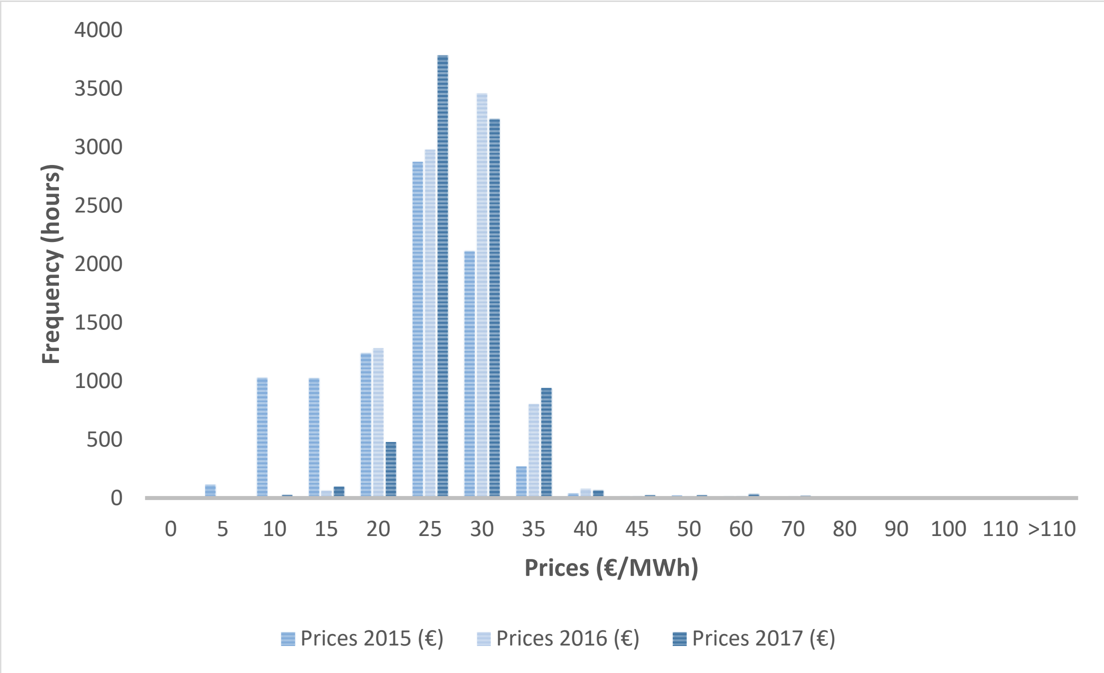

Figure 5. Histogram of spot market energy prices of 2015-2017.

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

3.1.3.2 Green certificates 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 [3].

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 28.4 TWh by the end of 2020. Sweden will finance 15.2 TWh and Norway 13.2 TWh. 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. For this study an average value of the green certificates is used (see Table 4)

The third 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 fees are related to two concepts:

1. Energy dependant tariff: it is obtained as a percentage of the energy price. It is obtained on a variable percentage of energy process.
2. Fixed tariff: different fee is applied for producers and consumers.

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

$$\text{Wind energy income}\left(\frac{€}{\text{MWh}}\right) = \text{Spotmarket price} + \text{Green certificate} +$$

$$+ \text{Green Guarantee} - \text{Tariff}_{\text{EnergyComponent}} - \text{Tariff}_{\text{Fixed}}$$

Equation 6

Next the values of green certificates, guarantees and tariffs used for the study are shown. These values correspond to 2016.

Table 4. Green certificate & tariff in Norway.

Green certificates and tariffs	
Parameter	**Value**
Green certificate	15.45 €/MWh
Tariff, energy component	-4% spot market price
Tariff, fixed component	-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 [4]. To take this into account a sensitivity analysis of this value has been done 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.

3.2 Electrolyser Data

An electrolyser is an electrochemical device that converters electricity into H_2. HAOLUS project will integrate a 2.5 MW PEM electrolyser developed by Hydrogenics. The main characteristics of the electrolyser used for the techno-economic simulations are summarised in Table 5.

Table 5. 2,5MW Hydrogenic electrolyser PEM data.

2,5 MW PEM Electrolyser	
Parameter	**Value**
Nominal Power	2.5 MW
Minimum Power	0.3 MW
Maximum Power	3.25 MW
Efficiency	see Figure 6
Efficiency degradation at rated power and considering 8000 h operations / year	2 %/year
Hydrogen delivery pressure	30 bar
Hydrogen production rate	45 kg/hour
Start-up time (cold start)	1200 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	60 MW/min
Standby consumption	1 kW
Calendar life	20 Years
Cycle life	5000 on/off cycles
	40,000 operation hours
CAPEX-electrolyser	1328 €/kW
OPEX per installed MW	60 €/MW year
Overhaul costs (*)	354 €/kW

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

The electrolyser efficiency is not a fix value but a curve that depends on the direct current (Idc) consumption of the stack. As it can be seen in the curves plotted in Figure 6, 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.

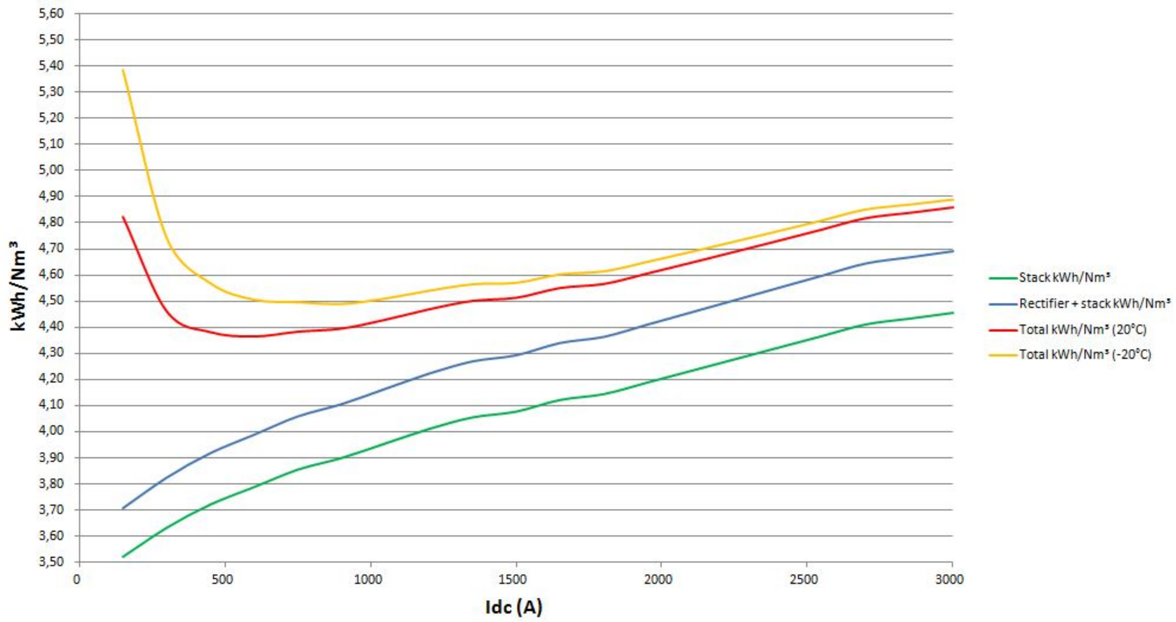

Figure 6. Electrolyser efficiency curve.

FCH 2 JU Multi-Annual Work Plan (MAWP) for years 2014-2020 has fixed several cost and performance targets for electrolysers. These targets have been considered in these studies and sensitivity analysis have been carried out according to next KPIs.

		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

Figure 7. FCHU MAWP 2014-2020 targets for electrolysers [3]

3.2.1 Electrolyser operation & degradation

Hydrogenics' electrolyser to be installed in Raggovidda has 3 operations modes:

1. *Off:* the electrolyser is not generating H_2 and is depressurized. There is no energy consumption.
2. *Standby:* the electrolyser is not generating H_2 but is pressurized. There is a small energy consumption (few kilo watts).
3. *On:* the electrolyser is generating H_2. The energy consumption will depend on the H_2 generation.

To shift from one operation mode to another the electrolyser takes some time and consumes some energy:

- *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 15 kW) the first 15 s to 2.5 MW (maximum) linearly.
- *Shut down time: 1 second.* This is the time to shift from production to standby.
- *Switch off time: 2 minutes.* This is the time to shift to off (depressurized).

For these studies it has been considered that the electrolyser never switches off, so that when it is not producing it remains in standby mode. Keeping the electrolyser in standby does not have any problem for the system and the only drawback is a small energy consumption in the range of 1 kW. This operation mode avoids continuously switching on/off the electrolyser, which consumes time, energy and nitrogen for purging. Additionally, the effect of the on/off operation strategy on the hourly base techno-economic studies is negligible. On the other hand, the real time optimal operations strategy will be studied in detail in "WP6 Control" and "WP8 Demonstration" work packages of HAEOLUS project.

The electrolyser suffers a gradual performance degradation associated to the usage. It has been considered an efficiency degradation of 2 % at rated power and per 8,000 h of operation. This efficiency degradation is a relative value, thus, e.g. if the efficiency is 98 % the efficiency degradation after 8,000 hours would be 1.96 %.

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 two parameters: 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 hour.

Once the electrolyser overpasses it 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.

3.3 Fuel cell

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 O2 and produces electricity, heat and water,

As part of the HAEOLUS project a 120 kW fuel cell will be installed intend to re-electrify the produced H_2 while the local H_2 market is developed. Considering that H_2 re-electrification is not the main purpose of the project and that the power rate of the fuel cell is too small in comparison with the wind farm and the electrolyser, the fuel cell has not been considered for the scenario analysis.

The fuel cell was manufactured by HYDROGENICs as part of INGRID (www.ingridproject.eu) EU cofounded project.

Table 6. 120 kW Hydrogenics fuel cell data

120 kW PEM Fuel Cell	
Parameter	**Value**
Nominal Power	120 kW
Minimum Power	12 kW (10%)
Maximum Power	132 kW
Efficiency	See graph
Peak Efficiency	50 %
Hydrogen consumption rate	9 kg/hour
Response time (warm start)	300 seconds
Warms start time	<5 seconds
Ramp rate up/down	<3 seconds to full power

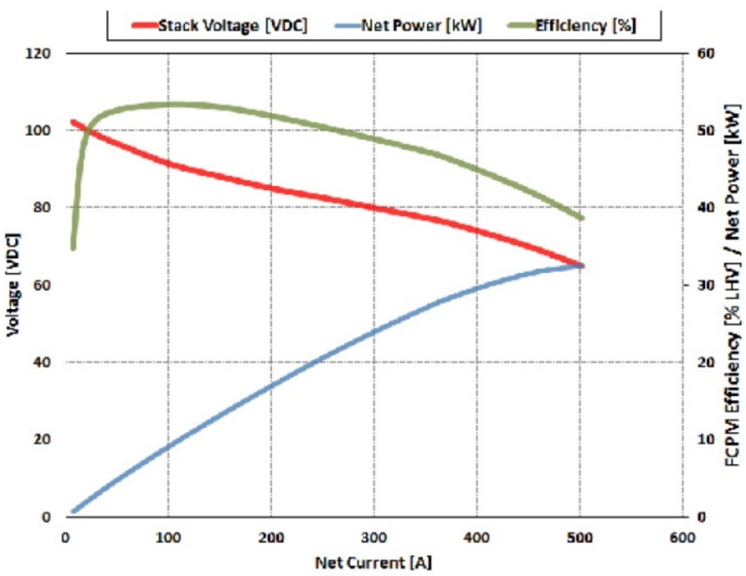

Figure 8. Fuel cell efficiency curve.

3.4 General financial data

Table 7 shows the financial data used for the studies.

Table 7. 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

4 Scenario 1. Optimal Hydrogen production

4.1 Introduction

This scenario consists on the production of H_2 at the minimum possible cost by means of a 2.5 MW electrolyser installed and operated within the Raggovidda Wind farm.

H_2 production costs have been calculated according to Equation 3 (Section 3.2) and taken into consideration the cost of the consumed electricity (energy produced by the wind farm) as described in section 4.1.3.2. It is important to note that this is the cost of H_2 at 30 bars at the exit of the electrolyser and without considering any further compression costs neither storage tank costs. In this study Equation 3 and Equation 4 are equivalent.

The electrolyser is operated according to the spot market electricity prices (see 4.1.3), producing H_2 when the energy prices are below a certain threshold. The main objective of the study is to analyse different operation strategies and evaluate the values of the price thresholds that show the lowest H_2 production costs. The objective is twofold:

1. Production of a minimum of 120 t 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 to the number of yearly working hours of the electrolyser. Different prices have been defined to determine the H_2 lowest production cost (≥120 t - 2.5 years).
2. *Variable threshold.* The threshold changes from day to day so that the minimum H_2 tonnes (120 t in 2.5years) are 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.

This scenario has been analysed for the following set of parameters:

- Electrolyser characteristics and costs according to Hydrogenics' and MAWP's targets for 2017, 2020 and 2023.
- As commented in section 4.1.3.2 Norway promotes renewable energy through a quota system including a certificate trading scheme. As the value of these certificates may vary a lot throughout next years, four reference value from 0 to 100 % have been considered.

4.2 Base case scenario: wind farm without electrolyser

As a first step the economic performance of the Raggovidda Wind farm without electrolyser has been calculated. This is the base case scenario and the results are used to evaluate and compare the economic performance of the wind-H_2. The study has been done on the basis of 2017 production and market data for a 20 years period.

Table 8 and Table 9 summarise the base case scenario configuration data and results. LCOE has been obtained according to Equation 2.

Table 8. Raggovidda wind farm economic performance results

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

Table 9. Scenario 1. Raggovidda wind farm economic performance results for different green certificates

	Base case Scenario: 45 MW 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	37.9 M€	20.4 M€	11.6 M€	3.7 M€

The results show that Raggovidda wind farm has a capacity factor of around 48 %, which is much higher than typical values for onshore wind that are in the range of 40 % [8]. This high utilization factor permits to obtain very competitive LCOE and hence high NPV. In this sense, Raggovidda is an outstanding location for wind farms, however as it has been explained in the introduction there are relevant power production restrictions. In this context H_2 technology could play a relevant role.

As it can be seen in Table 9 green certificates have a significant weight 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.

4.3 Electrolyser operation with fix price thresholds

This study is bases on operating the electrolyser according to fix energy price thresholds, so that whenever the price drops below a certain value the electrolyser starts producing H_2 at the maximum available power, consuming only energy produced by the wind farm never directly form the grid. As previously commented, two types of studies have been performed, with an operation strategy to produce 120 t in 2,5 years and with an operation strategy to optimize H_2 production costs.

As explained in section 4.2.1, the electrolyser operation strategy consists on keeping the electrolyser always ON, either in Standby or in Production. Whenever the electrolyser is in standby there is a small energy consumption due to auxiliaries but under these conditions the electrolyser reacts nearly instantaneously to operation signal. As the standby consumption of Hydrogenics' electrolyser as low as 1 kW, this consumption has been depreciated. The effect of this simplification is negligible, being the maximum annual standby consumption in the range of 8 MWh per year, with a cost around 160 € versus an annual energy income of around 5 to 7.5 M€. In any case, WP6 of HAEOLUS project will analyse the possibility to optimize this operation strategy.

With the aim of showing electrolyser operations strategies next figures show the electrolyser operation over several days with a price threshold of 40 €/MWh. Figure 9 shows the electricity spot market price and the threshold while Figure 10 shows the electrolyser activation when the price drops below the threshold. When possible, the electrolyser operates at maximum power, but when the wind farm production is below 2.5 MW the electrolyser power is adjusted to the maximum available wind power, as e.g. it happens on 10th February.

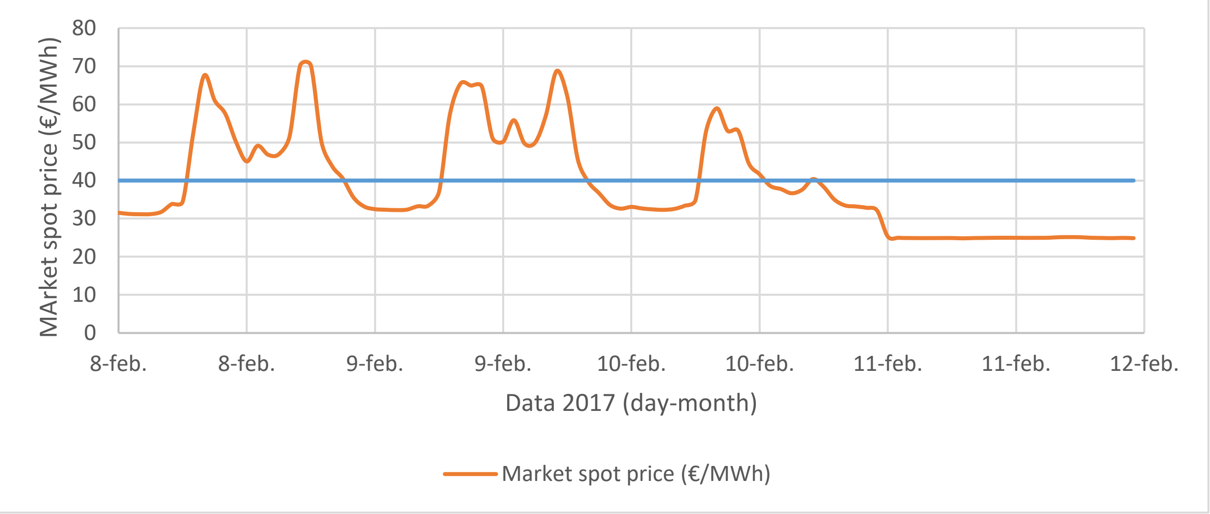

Figure 9. Spot market price and fixed threshold of 40 €/MWh.

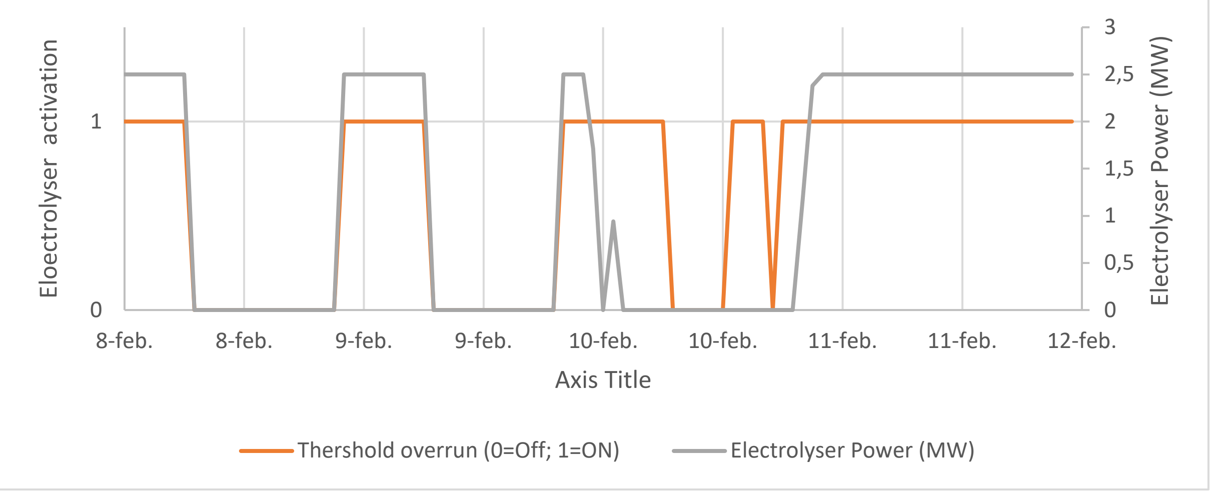

Figure 10. Electrolyser's activation (bool. on/off) and power (MW). Fixed threshold: 40€/MWh.

Figure 11 shows both the wind farm and the electrolyser power consumption with a fixed threshold of 40€/MWh. Likewise, Figure 12 shows a comparison of the electrolyser power for different threshold values. As it can be observed, when a threshold of 23 €/MWh is used the electrolyser does not enter in production within the 4 days. On the contrary, in the case of a threshold of 150 €/MWh, as long as the wind farm is generating, the electrolyser is always producing H_2.

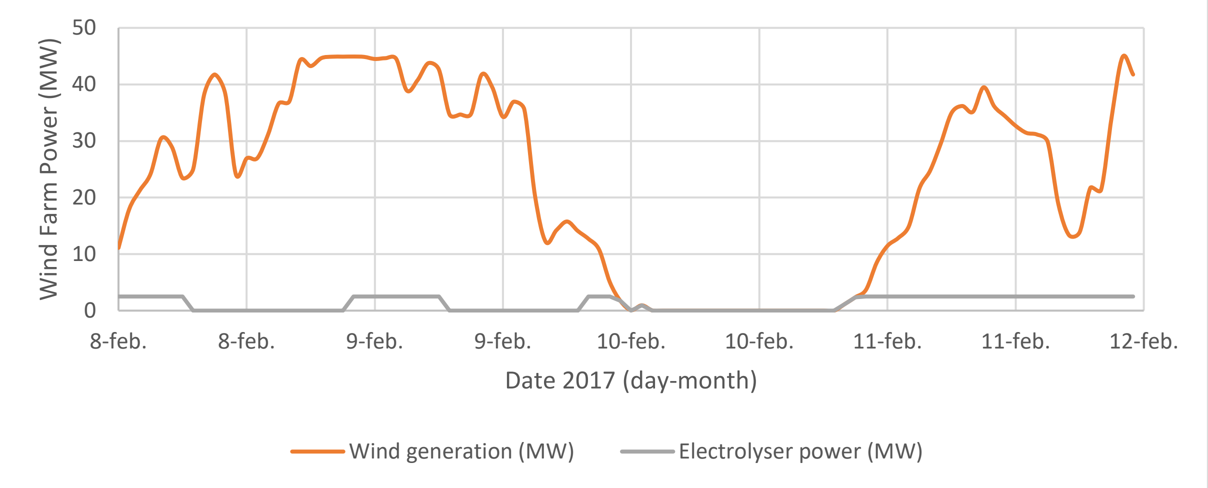

Figure 11. Wind Farm generated power & electrolyse useful power. Fixed threshold: 40€/MWh.

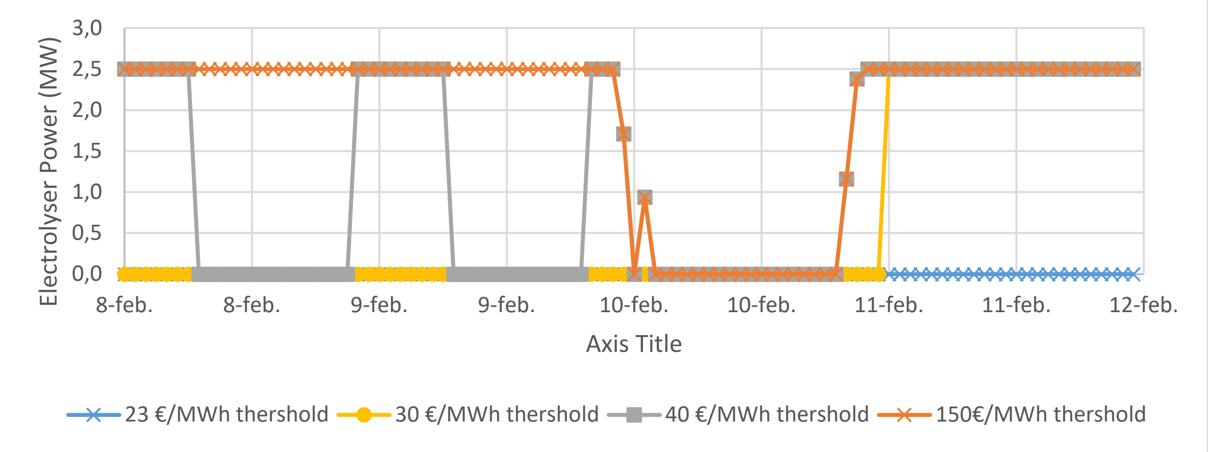

Figure 12. Electrolyse power (MW) time profile for different thresholds (€/MWh).

Several electricity price thresholds have been applied, from 23 to 150 €/MWh, analysing the amount and cost of produced H_2 and the utilization of the electrolyser. The value of 23 €/MWh corresponds to the case in which the H_2 production reaches around 120 t in 2.5 years (50 t per year) and 150 €/MWh is the threshold that keeps the electrolyser continuously producing.

Table 10 shows the main simulation results for a 50 €/MWh threshold and for the considered sensitivity parameters related to the green certificates and electrolyser characteristics.

Table 10. Scenario 1 Results summary for a fix price threshold strategy of 50 €/MWh.

		Base Case	2017	2020	2023
Wind Farm data					
Installed Power (MW)		45	45	45	45
CAPEX (M€)		40.5	40.5	40.5	40.5
OPEX. Annual (M€)		1.8	1.8	1.8	1.8
Annual Generated Energy (MWh)		190,805	190,805	190,805	190,805
Electrolyser data					
Installed Power (MW)		--	2.5	2.5	2.5
CAPEX (M€)		--	3.32	1.795	1.345
OPEX. Annual (M€)		--	0.15	0.15	0.15
Annual Generated H_2 (t)		--	331	336	340
Working hours (h)		--	7,836	7,836	7,836
Standby (h)		--	923	923	923
Integrated system data					
Annual injected energy (MWh)		190,805	172,096	172,096	172,096
Green certificates 13.1 €/MWh	**Annual Incomes (€)**	7,484,908	6,805,830	6,805,830	6,805,830
	NPV (€)	37,947,659	22,293,690	24,171,005	24,721,389
	H_2 production cost (€/t)	--	3,453.54	2,994.07	2,840.54
Green certificates 6.37 €/MWh	**Annual Incomes (€)**	6,200,791	5,624,459	5,624,459	5,624,459
	NPV (€)	20,374,263	6,443,390	8,320,705	8,871,089
	H_2 production cost (€/t)	--	3,073.40	2,619.59	2,470.48
Green certificates 3 €/MWh	**Annual Incomes (€)**	5,557,779	5,032,895	5,032,895	5,032,895
	NPV (€)	11,574,509	-1,493,535	383,780	934,164
	H_2 production cost (€/t)	--	2,883.04	2,432.07	2,285.17
Green certificates 0 €/MWh	**Annual Incomes (€)**	4,985,364	4,506,281	4,506,281	4,506,281
	NPV (€)	3,740,900	-8,559,048	-6,681,733	-6,131,349
	H_2 production cost (€/t)	--	2,713.59	2,265.14	2,120.21

On the one hand, as it can be seen in Table 10, for the considered spot market prices and operation threshold, H_2 production cost may decrease around 20 % when 2023 MAWP electrolyser targets are applied.

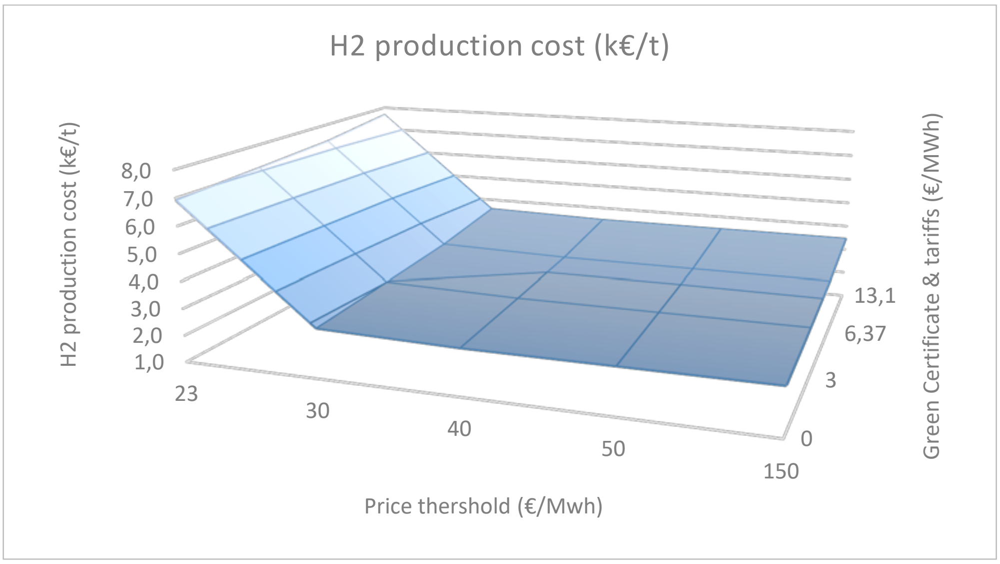

Figure 13. H_2 production cost (k€/t) with 2017 MAWP targets

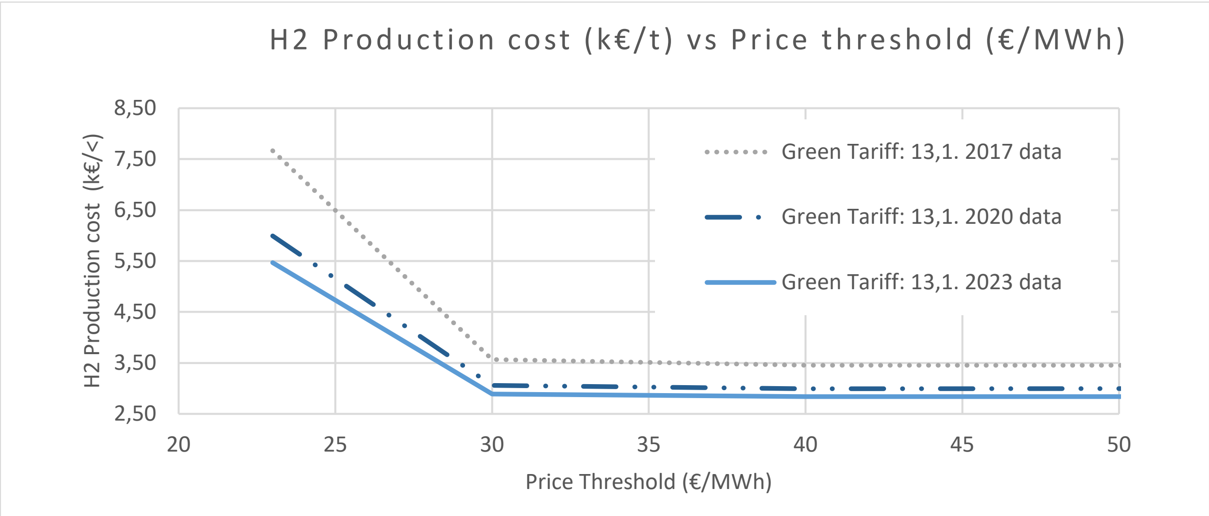

Figure 14. H_2 production cost (k€/t) vs Price threshold (€/MWh) for 2017-2023 MAWP targets

On the other hand, Figure 13 and Figure 14 show the LCOH2 for different price thresholds. As it can be appreciated the LCOH2 is lower for higher price thresholds, decreasing the cost form 7.50 k€/t down to 3.5 k€/. The fact that higher thresholds gives a better H_2 production cost, which a priori seems a contradiction, is due to the CAPEX of the electrolyser has much higher weight in the H_2 production cost than the OPEX and the cost of the consumed energy. In consequence, the operation strategy that assures a higher usage of the electrolyser, i.e. higher H_2 production (Figure 15), is the one that produces H_2 at the lowest possible cost, provided that there is a market for all the produced H_2.

As it can be seen in the graphs, thresholds above 30 € provide few LCOH2 reduction, this due to the increase of the utilization rate is small and the additional H_2 production is at high energy costs.

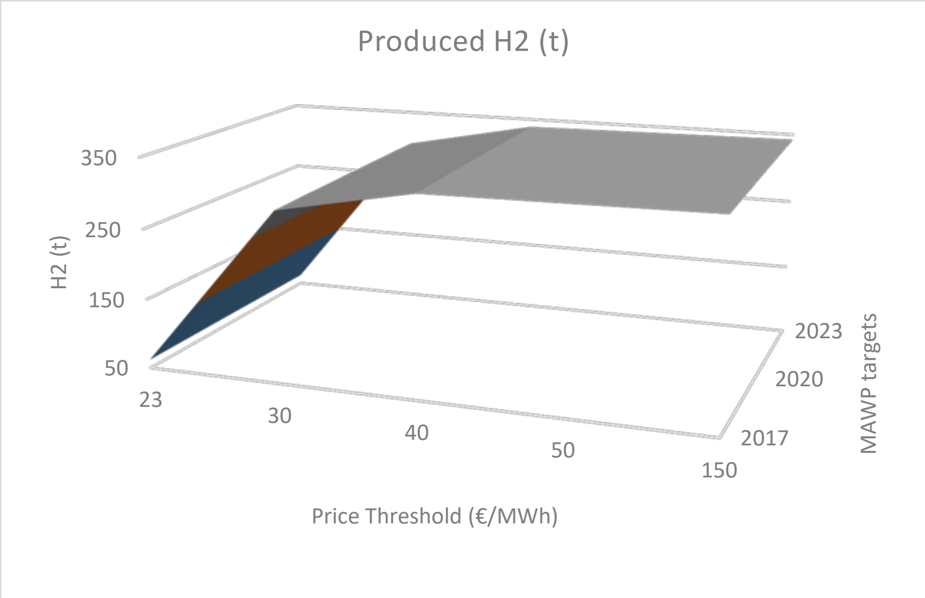

Figure 15. Generated H_2 (t) vs. price threshold (€/MWh) for 2017, 2020 and 2023 data.

4.3.1 Variable threshold

This operation strategy consists on operating the electrolyser a fix number of hours per day, by selecting for each day a different price threshold. This strategy is intended to produce H_2 uniformly and hence it is the most suitable one when there is a limited H_2 storage capacity and/or a continuous demand of H_2.

In this case the operation strategy is defined to adjust the electrolyser operation to produce a minimum of 120 t in 2.5 years, which approximately requires the electrolyser to operated 4 hours per day at full production capacity. I.e. for each day the four highest prices are determined and the lowest of these is chosen as the day threshold.

Next figures show the electrolyser operation strategy. Figure 16 shows the electricity spot market price and the variable price thresholds. As it can be appreciated the threshold varies daily and the electrolyser is activated when the price drops below the threshold. The electrolyser is activated 4 hours per day, either consecutive hours as on 9 or 10th February 2017, or non-consecutive as on 11th February 2017.

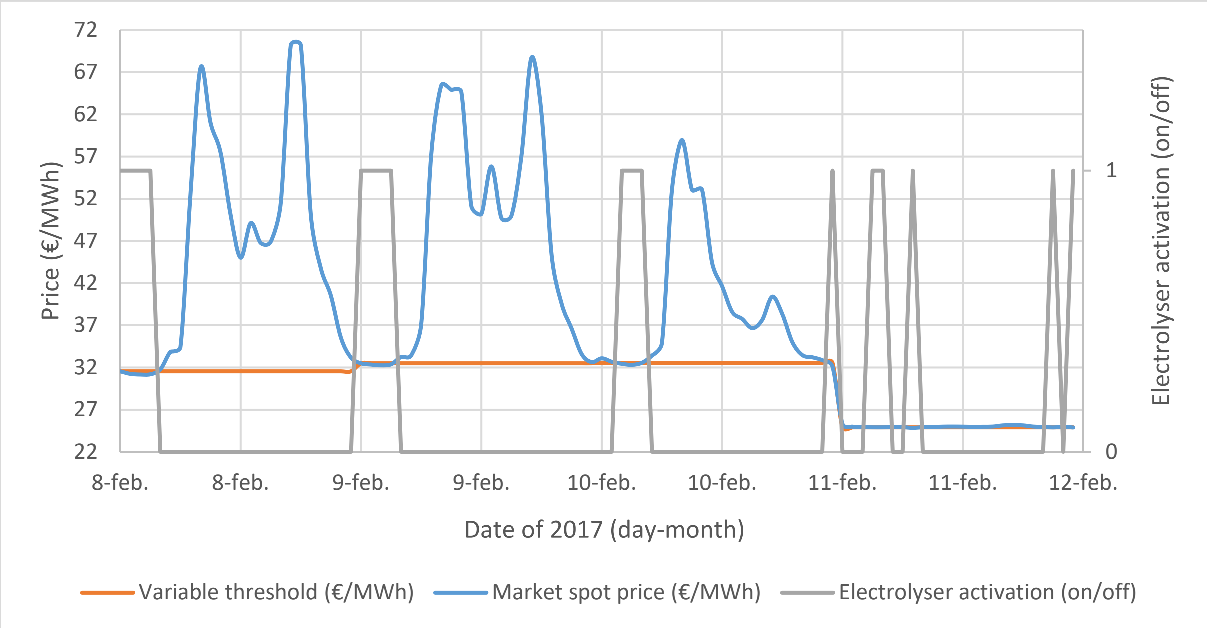

Figure 16. Market spot price (€/MWh) and electrolyser activation time profiles.

Figure 17 shows a comparison of the electrolyser power for the two implemented operation strategies, with a fixed threshold of 23 €/MWh and variable thresholds. Although the amount of yearly H_2 production is similar in both cases, as it can be appreciated the activation periods of the electrolyser differ.

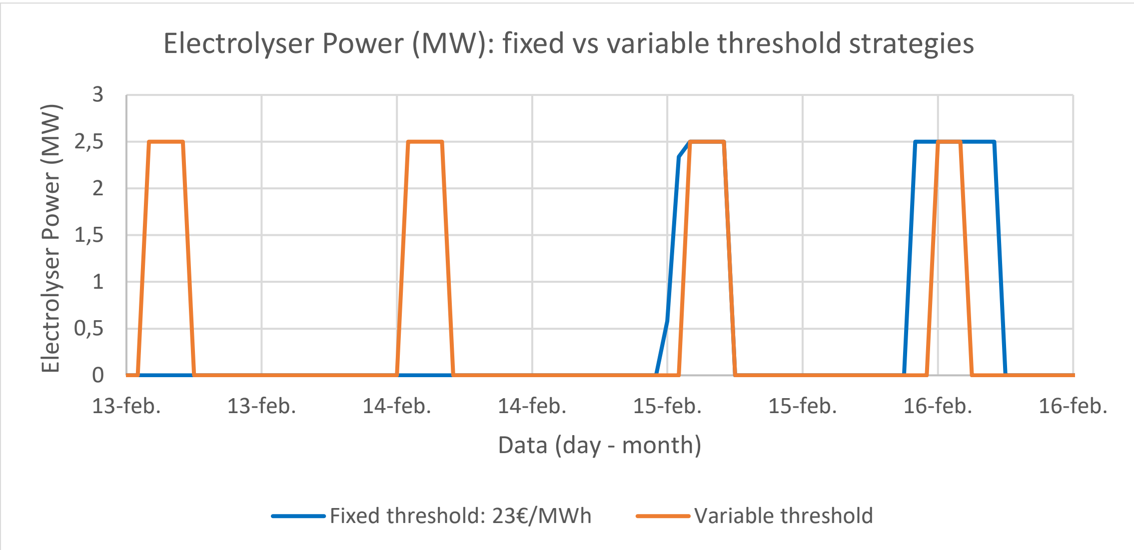

Figure 17. Comparison of the electrolyser power (MW) for the fixed threshold strategy (40€/MWh) and the variable threshold strategy.

Next table shows the results obtained with variable threshold for 4 hours daily operation and for a fix threshold strategy with a similar yearly H_2 production. As it can be appreciated there are few differences between both operation strategies. Taking this into consideration, the preferred option would be the variable threshold strategy, as it produces H_2 uniformly over the year and this would potentially require smaller storage tank volume.

Table 11. Scenario 1 Results summary for vaiable threshold strategy (4 production hours per day)

		Base Case	Fixed threshold 23 €/MWh	Variable threshold
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 (MWh)		190,805	190,805	190,805
Electrolyser data				
Installed Power (MW)		--	2.5	2.5
CAPEX (M€)		--	3.32	3.32
OPEX. Annual (M€)		--	0.15	0.15
Annual Generated H_2 (t)		--	62	58
Working hours (h)		--	1,498	1,372
Standby (h)		--	7,020	7,387
Integrated system data				
Annual injected energy (MWh)		190,805	187,293	187,525
Green certificates 13,1 €/MWh	**Annual Incomes (€)**	7,484,908	7,416,964	7,413,329
	NPV (€)	37,947,659	31,420,567	31,375,518
	H_2 production cost (€/t)	--	7,665.20	8,269.32
Green certificates 6,37 €/MWh	**Annual Incomes (€)**	6,200,791	6,131,271	6,126,047
	NPV (€)	20,374,263	14,170,597	14,104,221
	H_2 production cost (€/t)	--	7,285.38	7,889.21
Green certificates 3 €/MWh	**Annual Incomes (€)**	5,557,779	5,487,469	5,481,449
	NPV (€)	11,574,509	5.532,796	5,455,741
	H_2 production cost (€/t)	--	7,095.19	7,698.87
Green certificates 0 €/MWh	**Annual Incomes (€)**	4,985,364	4,914,352	4,907,623
	NPV (€)	3,740,900	-2,156,641	-2,243,203
	H_2 production cost (€/t)	--	6,925.88	7,529.43

4.4 Conclusions

This scenario basically consists on the operation of an electrolyser within the fence of Raggovidda wind farm, producing H_2 at the lowest possible cost according to the electricity spot market prices. The main general conclusion is that the operation strategies that show lower production costs (LCOH2), are those that have higher utilization rate of the electrolyser, this means those that produce higher amount of H_2.

Additionally, as it can be seen in Figure 18, it has been evaluated that there are few differences in the LCOH2 for the two implemented operation strategies, with fix or variable price thresholds

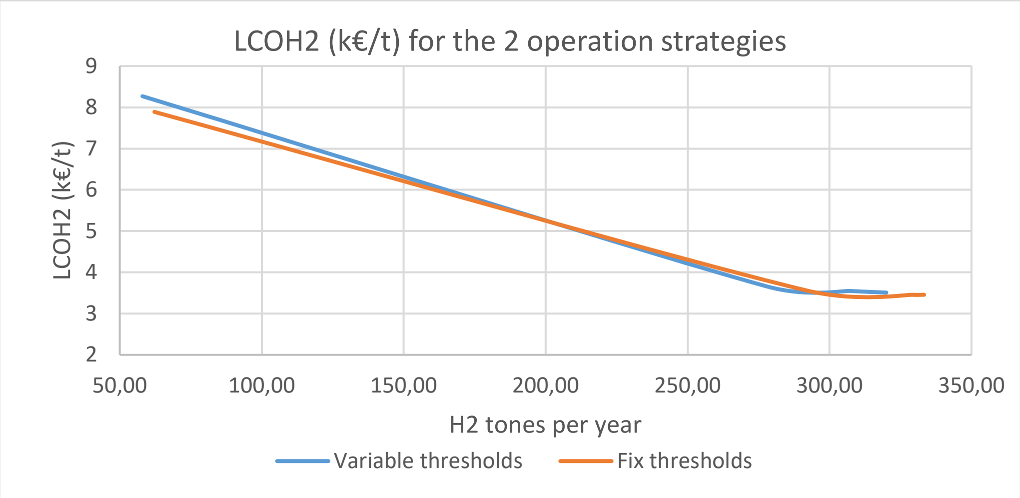

Figure 18. Comparison of the LCOH2 for the two operation strategies

The main reasons for these findings are as follows:

- Current electrolyser capital costs have much higher weigh on the H_2 production costs than the cost of the consumed energy.
- The electrolyser overhaul costs are much lower than initial capital expenditures, this benefits the operation strategies with high utilization rates.
- There is little room for optimizing the operation strategy due to the low variability of the electricity spot market prices in Norway. This, jointly with the effect of the CAPEX on the H_2 production cost, makes nearly negligible the difference between the applied operation strategies.

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.

5 Scenario 2. Congestions Management

5.1 Introduction

This scenario basically consists on producing H_2 by electrolysis when the wind farm production overpasses the power connection point limit, either administrative of physical. Thus, the electrolyser produces H_2 with an energy that otherwise would be wasted.

This study is of high relevance because nowadays Raggovidda has a granted concession of 200 MW, while the Varanger Peninsula export capacity is limited to 95 MW. This is a very relevant restriction given that the location has a remarkable wind resources, which would permit to obtain high capacity factors and low LCOE.

As there is no public information about the wind resources in other potential locations, current data from Raggovidda wind farm has been used as reference. Just for analysis purposed the export limit has been fixed at 45 MW and higher power wind farms have been evaluated by extrapolating Raggovidda's data. These suppositions are valid for a first evaluation of the benefit and possibility of using the curtailed energy for H_2 production, however more detailed analysis would require using detailed data of the wind resource in the new potential wind farm locations.

As for the previous scenario, this study analyses different wind-H_2 solutions by comparing the LCOH2 calculated according to the Equation 4 of section 3.2. The cost is calculated to equal the NPV of the wind-H_2 system to the base case system, which does not include electrolyser.

$$LCOH2\left(\frac{€}{\text{kg}}\right) = \frac{\text{NPV}_{\text{Base Case}} - \text{NPV}_{\text{wind}+H_2}}{\sum_{i=1}^{n} H_2 \text{ production}_i \cdot \left(\frac{1+e}{1+d}\right)^i}$$

In this case, differently from the previous scenario, the LCOH2 is affected not only by the CAPEX of the electrolyser but also by a portion of the additional investment and operational cost related to the oversizing of the wind farm. Additionally, in this case as the H_2 is produced with the surplus of energy that cannot be fed to the grid, as the cost associated to this energy is zero, this aspect does not affect to the LCOH2.

As in the previous study, this scenario has been analysed for the following cases:

- Electrolyser characteristics and costs according to Hydrogenics' data and MAWP's targets.
- The impact of different green certificates & tariffs (Norway) have been also considered; expected mean value (13.1 €/MWh), significant reductions (6.37 €/MWh and 3 €/MWh) and without green certificates & tariffs (section 4.1.3.2).

5.2 Simulation results

5.2.1 Analysis of optimal wind farm size

First, it has been analysed which is the optimal size of the wind farm without electrolyser and with a 45 MW 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 shows the higher NPV has been considered as the optimal one.

Table 12 summarised the results obtained for several wind farm sizes. As it can be seen, for current RES remuneration scheme, a wind farm of 47.5 MW would be the one with highest NPV. The 70 % of the additional generated power is fed to the grid while the other 30% 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 for wind-H_2 solutions evaluation.

Table 12. Results of Raggovidda wind farm sizing with 45 MW export restriction

Base case: Raggovidda wind farm size with 45 MW export restriction					
Installed Power (MW)		45.0	47.5	50.0	52.5
CAPEX (M€)		40.5	42.3	45	47.3
OPEX, Annual (M€)		1.8	1.9	2	2.1
Annual Generated Energy (MWh)		190,805	201,405	212,005	222,606
Annual Energy Injected to the grid (MWh)		190,805	198,182	204,114	209,238
Annual energy curtailment (MWh)		0	3,223	7,891	13,368
Green certificates 13.1 €/MWh	Annual Incomes (M€)	7.48	7.72	8	8.2
	NPV (M€)	37.9	38.3	38.0	37.2
Green certificates 6.37 €/MWh	Annual Incomes (M€)	6.20	6.44	6.63	6.79
	NPV (M€)	20.4	20.4	19.6	17.9
Green certificates 3 €/MWh	Annual Incomes (M€)	5.56	5.77	5.94	6.09
	NPV (M€)	11.6	10.2	9.1	7.4
Green certificates 0 €/MWh	Annual Incomes (M€)	4.98	5.18	5.33	5.46
	NPV (M€)	3.7	2.1	0.7	-1.0

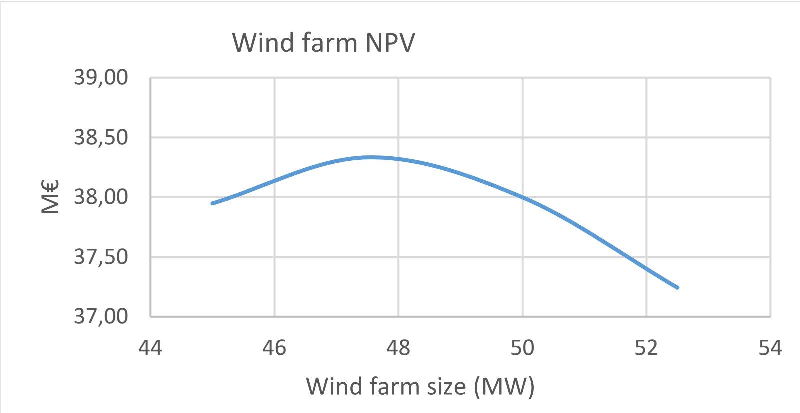

Figure 19. NPV for several wind farm sizes for 45 MW export restriction (2017 MAWP targets and market data)

Figure 20 shows the NPV for all the analysed configurations. It can be observed how the energy price affects to the profitability of the wind farm and hence to the optimal size. Thus, for the case of green certificates 50 % below current values it does not make sense to increase the wind farm size over the export limit.

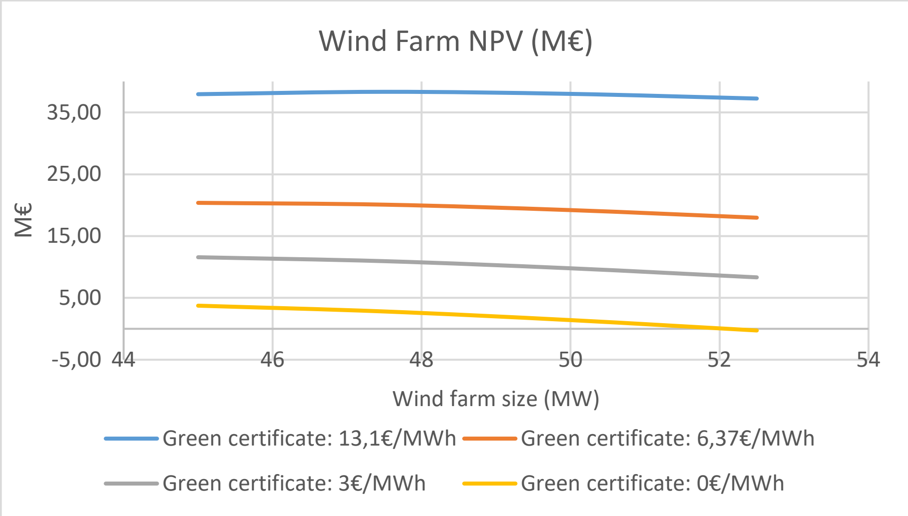

Figure 20. Base case: NPV of the Wind Farm (M€).

5.2.2 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. As in the previous scenario, 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 45 to 57.5 MW in 2.5 MW steps and electrolysers from 2.5 to 12.5 MW in 2.5 MW steps have been evaluated. The electrolyser maximum size has been limited for all the cases to the maximum curtailed power, this is the difference between the installed wind power and the power connection point export limit. Table 13 summarises the evaluated alternatives:

Table 13. Scenario 2 Wind-H_2 evaluated alternatives

Wind Farm Power (MW)	Electrolyser Power (MW)
47.5	2.5
50.0	2.5 / 5
52.5	2.5 / 5 / 7.5
55.0	2.5 /5 / 7.5 / 10
57.5	2.5 / 5 / 7.5 / 10 / 12.5

Figure 21 and Figure 22 show the H_2 production costs for 2017 and 2020 MAWPS electrolyser targets.

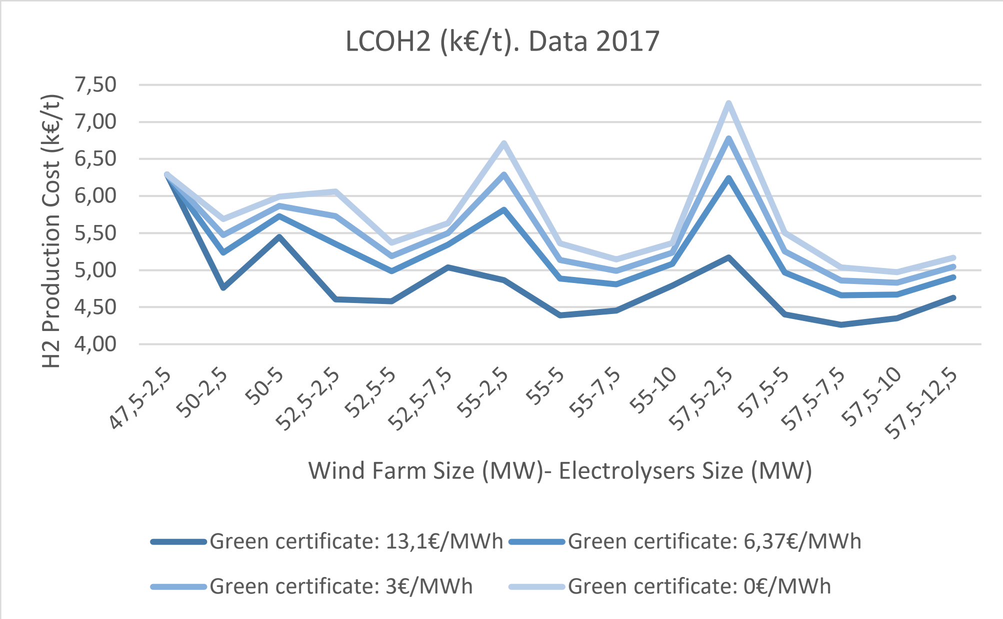

Figure 21. Scenario 2. LCOH2 with 2017 MAWP electrolyser targets

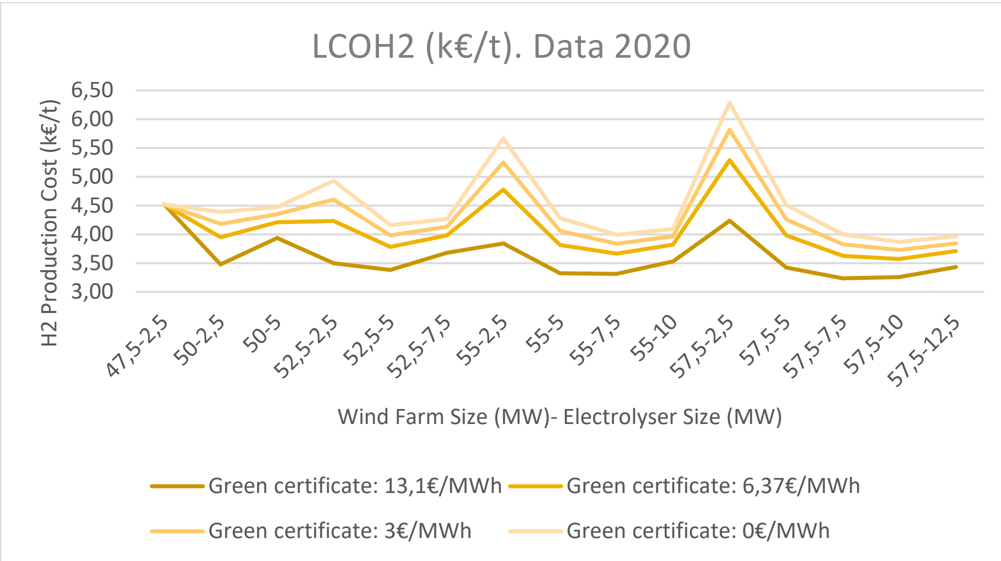

Figure 22. Scenario 2. LCOH2 with 2020 MAWP electrolyser targets

As it can be appreciated the LCOH2 decreases with the increase of green certificates, which is the opposite trend of the previous scenario. This effect on the H_2 cost is because of 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.

The above figures show that the LCOH2 significantly decreases for electrolyser characteristics according to MAWP 2020 targets, this is due to the high weight of the electrolyser CAPEX in the cost of H_2.

There are several solutions that have similar LCOH2, in the range of 4.5 k€/t, so that for selecting the most suitable solutions other aspects should be considered, as the H_2 demand or the required storage tank size. Figure 23 shows the big difference in the annual H_2 production achieved by the analysed configurations. At this respect it is important to highlight that the calculated LCOH2 only makes sense if there is a market for the produced H_2.

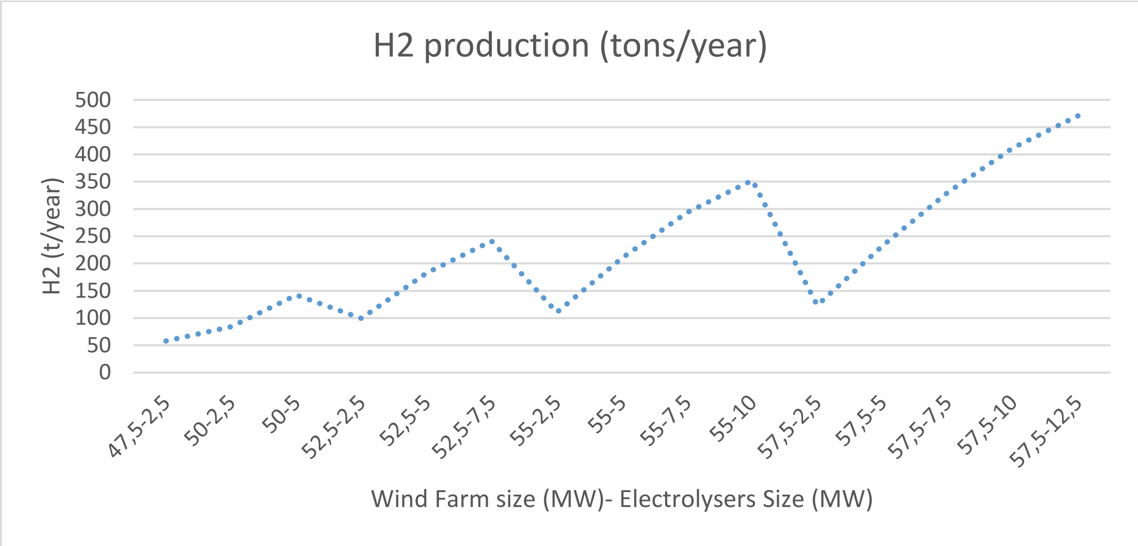

Figure 23. Scenario 2. H_2 yearly production

As it can be seen in Figure 24, most of the curtailment events happen with the wind farm working at maximum power, so when then electrolyser frequently works at maximum power. However, given the low number of hours with curtailments and the high weight 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 loses due to the power connection point congestion are not fully eliminated.

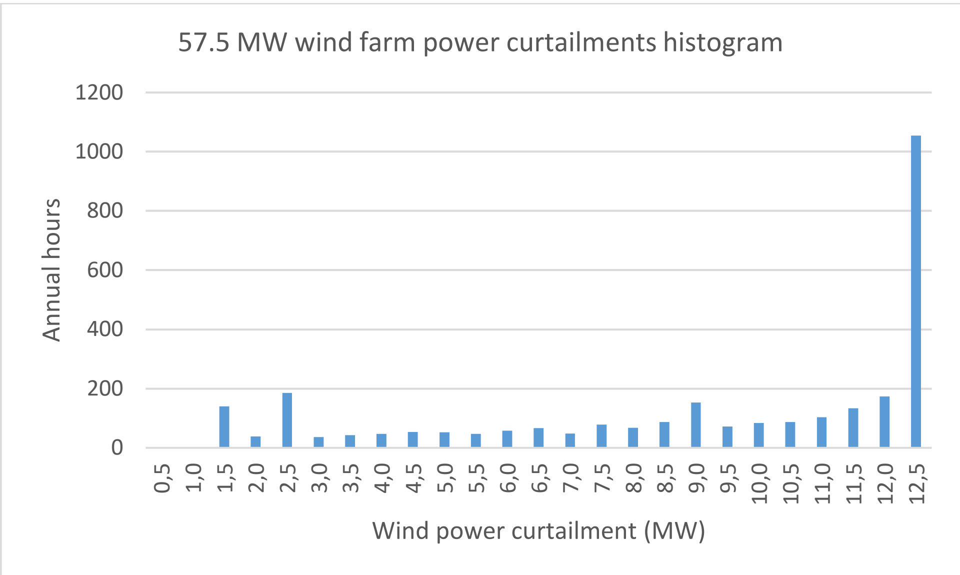

Figure 24. Scenario 2. 57.5 wind farm power curtailments histogram

Table 14 summaries the results for the most relevant configurations for 2017 MAWP electrolyser targets.

Table 14. Scenario 2. Summary of results

		Base Case 47.5 MW wind farm	57.5 MW Wind Farm	47.5-2.5 MW Wind-H_2 System	57.5-7.5MW Wind-H_2 System
Wind Farm data					
Installed power (MW)		47.5	57.5	47.5	57.5
CAPEX (M€)		42.3	51.8	42.3	51.8
OPEX. Annual (M€)		1.9	2.3	1.9	2.3
Annual generated energy (MWh)		201,405	243,806	201,405	243,806
Annual energy injected to the grid (MWh)		198,182	217,779	198,182	217,779
Annual electrolyser consumption (MWh)		--	--	3,223	18,537
Annual energy curtailed (MWh)		3,223	26,027	0	7,490
Electrolyser data					
Installed power (MW)		--	--	2.5	7.5
Mean power in production (MW)		--	--	2 (80 %)	6.4 (85 %)
CAPEX (M€)		--	--	3.32	9.96
OPEX. Annual (M€)		--	--	0.15	0.45
Annual generated H_2 (t)		--	--	57.94	330.16
Working hours (h)		--	--	1,639	2,910
Standby (h)		--	--	7,112	5,849
Raggovidda integrated system data					
Green certificates 13,1 €/MWh	**Annual income (M€)**	7.58	8.587	7.58	8.586
	NPV (M€)	38.3	34.86	33.34	19.1
	H_2 production cost (k€/t)	--	--	6.29	4.26
Green certificates 6,37 €/MWh	**Annual income (M€)**	6.25	7.092	6.25	7.091
	NPV (M€)	20.08	14.80	15.09	-0.9
	H_2 production cost (k€/t)	--	--	6.29	4.66
Green certificates 3 €/MWh	**Annual income (M€)**	5.58	6.344	5.58	6.343
	NPV (M€)	10.94	4.76	5.95	-11.02
	H_2 production cost (k€/t)	--	--	6.29	4.86
Green certificates 0 €/MWh	**Annual income (M€)**	4.98	5.67	4.98	5.67
	NPV (M€)	2.80	-4.18	-2.18	-19.59
	H_2 production cost (k€/t)	--	--	6.29	5.04

5.3 Conclusions

From the obtained results it can be concluded that considering the stable and strong wind resources in Raggovidda and the current remuneration scheme, it could be 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 to produce H_2 by electrolysis, obtaining very competitive H_2 production cost in the range of 4-5 €/kg, below the costs of operating the electrolyser as an ordinary consumer.

The results have shown that for the case of Raggovidda the electrolyser utilization factor is very low, spending the 75 % 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 the cost by increasing the production. The combination of operation strategies for congestion management and for H_2 production at low energy costs, could significantly reduce these costs.

6 Conclusions and next steps

Two operational scenarios related to the production of H_2 by electrolysis in the Raggovidda wind farm have been analysed. H_2 production costs have been calculated for several configurations and operation strategies, evaluating also the impact on the costs of electrolyser characteristics according to MAWP targets for 2017-2023 and the reduction of feed in tariffs for renewable energies.

The obtained results show that the obtained costs of H_2 production, in the range of 4 to 6 €/kg, are competitive according to current state of the art. There is a clear benefit related to deployment and operation of the electrolyser inside the wind farm, thus avoiding additional grid connection fees and having access to very competitive electricity costs. Additionally, the electrolyser can enhance the techno-economic operation of the wind farm, facilitating the grid integration and management of production congestions.

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

- Combination of electrolyser operation strategies related to congestion management (scenario 2) and production at optimized electricity cost (scenario 1).
- Analyse the possibility of operating the electrolyser for frequency regulation services, which could allow to produce H_2 at more competitive costs.
- Replicate the studies for other locations and on the basis of first experimental results.

7 References

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