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Value of green hydrogen when curtailed to provide grid balancing services

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HIGHLIGHTS

- Defined a metric independent of electrolyser cost or hydrogen price, which are a large source of uncertainty.
- Analysed the potential for grid services in multiple markets with real data for prices and wind power.
- Presented the separate contribution of grid services, spot prices and tariffs in the value of curtailed hydrogen.

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ABSTRACT

This paper evaluates the potential of grid services in France, Italy, Norway and Spain to provide an alternative income for electrolysers producing hydrogen from wind power. Grid services are simulated with each country's data for 2017 for energy prices, grid services and wind power profiles from relevant wind parks. A novel metric is presented, the value of curtailed hydrogen, which is independent from several highly uncertain parameters such as electrolyser cost or hydrogen market price. Results indicate that grid services can monetise the unused spare capacity of electrolyser plants, improving their economy in the critical deployment phase. For most countries, up-regulation yields a value of curtailed hydrogen above 6 €/kg, over 3 times higher than the EU's 2030 price target (without incentives). However, countries with large hydro power resources such as Norway yield far lower results, below 2 €/kg. The value of curtailed hydrogen also decreases with hydrogen production, corresponding to the cases of symmetric and down-regulation.

Abbreviations: aFRR, Automatic Frequency Restoration Reserve; FCR, Frequency Containment Reserve; LCOH, Levelised Cost of Hydrogen; mFRR, Manual Frequency Restoration Reserve; MSD, Dispatching Services Market; PEM, Proton-Exchange Membrane; RR, Replacement Reserves; TSO, Transmission System Operator.

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Nomenclature

E	Energy, MWh
p	Price, €/MWh or €/MW (by context)
T	Tariffs & incentives, €/MWh
P	Power, MW
V	Market volume, MW
A	Activated capacity, MWh
H	Hydrogen mass, kg
I	Income, €
t	Time, h
Indices	
$\uparrow$	Up-regulation
$\downarrow$	Down-regulation
$\uparrow\downarrow$	Symmetric regulation
0	Reference case
act	Energy activation component
cap	Power capacity component

Introduction

Hydrogen as an energy carrier has long been considered an important opportunity for the decarbonisation of energy systems, and has been enjoying increased interest from the industry in recent years.

The deployment of hydrogen technologies has been marred from the start from the well-known “chicken-and-egg” problem. On one hand, private companies are unwilling to build hydrogen refuelling stations without customers. Conversely, customers expect this infrastructure to be deployed before acquiring hydrogen vehicles. Even when this infrastructure is established, customers may hesitate, doubting it will remain in operation for long.

Electrolysers are expected to meet a continually increasing hydrogen demand as related technologies are deployed. As it takes 1–2 years to deploy a new electrolyser, extra capacity will be required to fulfil demand during this lead time. Exploiting this extra capacity would improve the economic viability of electrolysers.

Grid balancing services

Electricity fed into a power grid must be consumed at the same time it is produced: any imbalances must be compensated in real time by power reserves. Traditionally, this has been solved by mandating power plants to maintain some reserve that can be rapidly dispatched in case of overproduction (“down-regulation”) or overconsumption (“up-regulation”). Regulations vary across countries, but this reserve is usually remunerated in some way.

As more and more intermittent wind and solar power displace fossil-fuelled plants, instabilities in the electrical grid are likely to increase [1]. As these intermittent sources are by nature not controllable, they cannot directly provide any grid services (other than down-regulation by curtailing their production, which is however wasteful).

One possible solution to increase grid stability is energy storage systems. For example, despite power shortages during hours of peak demand, there is an annual surplus of energy in Norway's Finnmark region [2]: a storage system would shift energy from hours of excess production to hours when more power is required. Hydrogen production by electrolysis, with its short ramping times, can act as such a storage system, and contribute to the European Union's renewable energy strategy [3,4].

The Haeolus project

Haeolus is an EU-funded project that aims to increase the reliability of intermittent wind power through energy storage in form of hydrogen. The project operates a hydrogen system, sketched in Fig. 1, comprising a 2.5 MW electrolyser and a 100 kW fuel cell directly connected to the Raggovidda wind park in Berlevåg, Norway [5]. The electrolyser is housed in a standard 40-foot container, even though the stacks themselves have a much smaller footprint; more technical details were published by Santos and Marino [6].

The Raggovidda wind park consists of 15 turbines, each with a capacity of 3 MW. While Raggovidda has the highest capacity factor of all wind parks in Norway [7], the grid in the area is too weak to handle future expansions. The operator has already been granted concessions for a total of 200 MW of installed wind power capacity, while a bottleneck restricts export out of the local grid to 95 MW [8].

Literature review

Several authors have previously studied the idea of providing frequency regulating services from an electrolyser to improve its overall economy.

An early study by Guinot et al. [9] evaluated the levelised cost of hydrogen (LCOH) for an electrolyser plant in France. LCOH would be reduced by at most 2% by the provision of grid services. The main reason for this disappointing result is the high electrolyser cost, 3.4 €/W, now dated: for comparison, Haeolus' budget is about 1 €/W.

Nistor et al. [10] investigated the economical perspective of hydrogen refuelling stations located in the United Kingdom with on-site hydrogen production, and compared grid-connected production units to a wind-hydrogen system. They concluded that while a wind-hydrogen system provides the lowest per-unit cost of hydrogen, a combined grid and wind-energy system would reach higher electrolyser utilisation and more reliable delivery of hydrogen.

A few years later, Larscheid et al. [11] (ELYntegration project) found more promising results applying a detailed model of the German grid. Their conclusions were that provision of grid services was able to increase the electrolyser utilisation ratio, especially at low hydrogen prices.

A report by Chardonnet et al. [12] considered electrolysers in multiple European countries, including Italy and France. They concluded that grid services could have a significant economic impact, as the cost of providing them is relatively low.

Allidières et al. [13] presented a bird's eye analysis of the potential of electrolysers providing grid services, this time

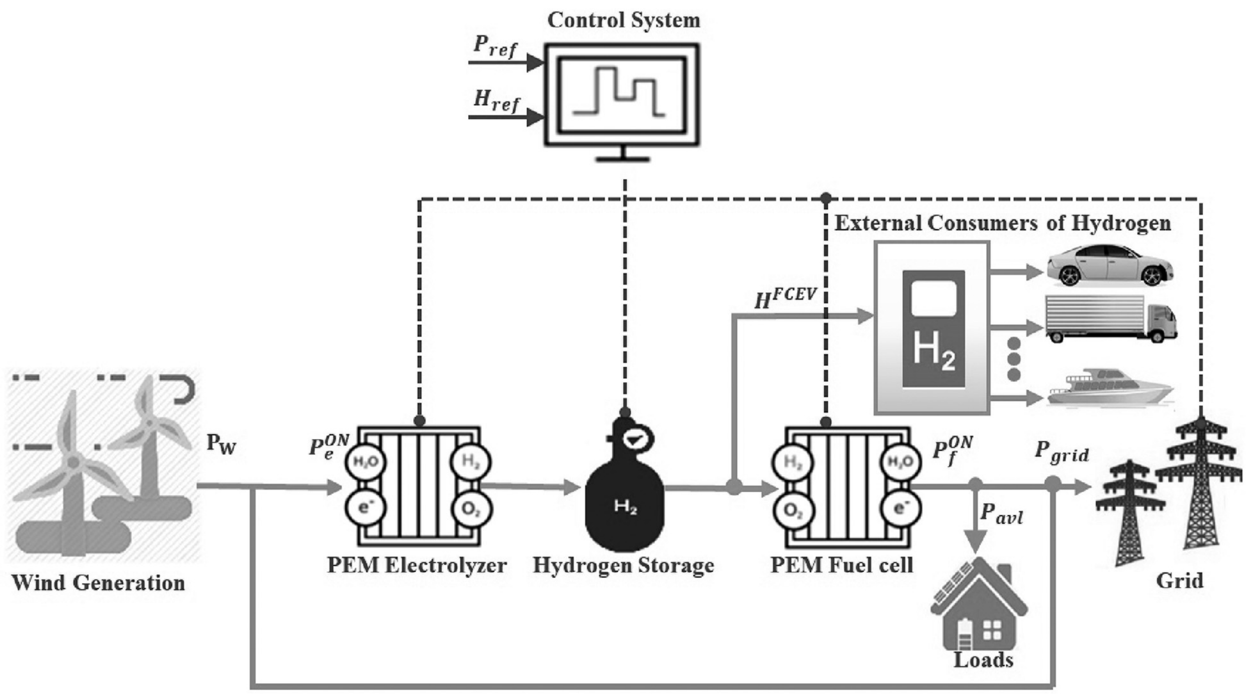

Fig. 1 – The Haeolus hydrogen system as operating in Berlevåg, Norway. For this study, the fuel cells have not been considered, and all hydrogen is assumed sold to external consumers.

specifically focusing on PEM technology rather than alkaline as previous authors had. Allidières et al. were positive about the outlook of the proposition, but their paper did not quantify its economic potential.

Alshehri et al. [14] reviewed the European ancillary services market, and investigated how PEM electrolysers and fuel cells could be introduced into it. They concluded that hydrogen technology is able to participate in the future European Frequency Containment Reserve (FCR) and automatic Frequency Restoration Reserve (aFRR) markets, and would contribute to increased stability of the grid. A simplified simulation of a part of the Dutch grid showed that replacing conventional synchronous generators with PEM electrolyzers and fuel cells would allow for faster containment of frequency deviations and less oscillation in grid frequency.

Santos and Marino [6] considered how to operate an electrolyser at Raggovidda and local grid congestion issues. They concluded that hydrogen cost could be reduced by expanding wind power capacity beyond the export capacity of the grid, increasing electrolyser utilisation.

Santos et al. [15] expanded the research scope with an analysis of wind farms in Smøla and Raggovidda, Norway and Moncayuelo, Spain. The conclusion for the Smøla case is similar to the Raggovidda case, where low electrolyser utilisation means that small units are the most profitable; however, congestion management leads to very high production prices for hydrogen for this case. In the Moncayuelo case, the inclusion of frequency regulation for the Spanish grid only marginally reduced the production cost of hydrogen, although operation strategies were not optimised.

Novelty and scope

This paper quantifies the economic potential of frequency regulating services for electrolysers within the fence of wind parks, both in Haeolus' actual location in Norway and at similar sites in Spain, Italy and France. Due to the fast ramping characteristics of electrolysers, we focus on faster, automatic services, which are usually also the more profitable ones. Haeolus' electrolyser is relatively small compared to the wind park, so we will also consider a hypothetical one as large as the wind park itself (45 MW).

We propose a new metric to measure the value of grid services provided by electrolysers: the value of curtailed hydrogen, i.e. the income realised by the wind park operator by exporting power and providing grid services instead of producing hydrogen. This approach has the advantage of being independent from uncertain electrolyser properties such as investments, operating costs, lifetime, etc.

Most of the previous literature has focused on the calculation of LCOH in scenarios with combined hydrogen production and provision of grid services, necessarily integrating variables such as the electrolyser CAPEX into the results. With our approach, we are able to determine the value of grid services on their own, which is a more interesting result for a hydrogen production plant that needs to make a decision on how to employ their spare capacity.

This paper considers only frequency control services, i.e. not production or consumption of reactive power (voltage control). Whereas voltage control can be provided by electrolyser plants, this would be more related to the operation of the rectifiers rather than the electrolyser themselves [14].

Methods

For a wind park with a nominal capacity identical to Raggovidda (45 MW) and containing an electrolyser unit, we will consider one reference case and three grid-servicing cases:

Reference The electrolyser produces hydrogen as long as the wind park is able to provide at least the electrolyser's minimum operating power, up to its full capacity. Energy beyond this is sold on the spot market.

Up-regulation The electrolyser operates at maximum power capacity as in the reference case, but sells its up-regulating capacity on the grid service market and reduces its power consumption when required.

Symmetric regulation The electrolyser sells an equal amount of up- and down-regulating capacity, operating therefore at a point close to half its capacity and increasing or reducing its power consumption when required.

Down-regulation The electrolyser sells its full capacity for down-regulation, operating close to its minimum power and increasing its power consumption when required.

For each case, we consider two sizes for the electrolyser: 2.5 MW, which is the same of the Haeolus project's electrolyser, and 45 MW, which is the same size of the wind park. Note that the larger electrolyser size will be limited by the same minimum power as the smaller one, i.e. 0.3 MW, since it is assumed that the larger plant consists of smaller modular units; idling PEM electrolyser stacks can be brought online in a few seconds.

The input data for the analysis are historical time series of wind energy production (E_{wind}, MWh), production tariffs and incentives (T, €/MWh), total market capacity (V, MW) and actually activated capacity (A, MWh), spot price (p_{spot}, €/MWh), capacity price (p_{cap}, €/MW), and activation price (p_{act}, €/MWh).

Data series for capacity, activation and relative prices may be different for up- and down-regulation. Data series are usually available with hourly discretisation, though exceptions do occur (France, in this paper, whose data is half-hourly). It is important that data for wind power are chronologically aligned with grid service data series, as the availability or lack of wind power may have a direct effect on the market and cause significant correlations.

Not all regimes are actually implemented in all analysed countries (e.g. Northern Norway implements only symmetric regulation): the missing ones will be simulated based on the available data. Note that some grid operators price symmetric capacity per MW in *both* directions (e.g. Norway): the price for one MW in up- or down-regulation will therefore be assumed to be half of one MW in symmetric regulation.

Value of curtailed hydrogen

In this paper, we introduce a different metric for the value of grid services, i.e. the *value of curtailed hydrogen*, i.e. hydrogen that was not produced due to participation in the grid-service market. This is calculated according to the following formula:

$$p_{H_2} = \frac{I - I_0}{H_0 - H} \tag{1}$$

where I is the income from sales of energy on the spot market and grid services, and H is the amount of produced hydrogen; the 0 subscript denotes the reference case in which the electrolyser is run at maximum available power and no grid services are provided.

The key advantage of equation (1) is that using a differential approach we can ignore a large number of uncertain parameters such as electrolyser cost and maintenance, which are assumed to be identical in both reference and grid-servicing cases, thus cancelling each other out in the expression $I - I_0$. This makes our results more general and less sensitive to technological developments than studies based on e.g. LCOH. In addition, we do not need to make any hypotheses on the price of hydrogen actually sold, which is an especially volatile estimate.

Reference case

In the reference case, the power used in hydrogen production is given by:

$$P_{H_2} = \begin{cases} P_{H_2}^{max} & \text{if} \quad P_{H_2}^{max} \le P_{wind} \\ P_{wind} & \text{if} \quad P_{H_2}^{min} < P_{wind} < P_{H_2}^{max} \\ 0 & \text{if} \quad P_{wind} \le P_{H_2}^{min} \end{cases} \tag{2}$$

where $P_{H_2}^{min}$ is the minimum operating power of the electrolyser, and assumed to be 0.3 MW. Hydrogen production is found by assuming a fixed production efficiency of $52\,\text{kWh/kg}_{H_2}$, a value targeted for PEM electrolysers in the near future [[16], p. 153]:

$$H_0 = \sum \frac{E_{H_2}}{52\,\text{kWh/kg}} \tag{3}$$

where $E_{H_2} = P_{H_2}\Delta t$, and Δt is the discretisation step of the data set (typically 1 h, half an hour, or 15 min); the $\sum$ operator is meant to apply to the whole data series, here and in the following equations. While in reality production efficiency will vary with stack current, temperature, production pressure, accurate efficiency curves are kept confidential by manufacturers; in any case, using this representative average value should not affect the results significantly.

Income in the reference case is due to spot sales minus tariffs, summed over the entire data series:

$$I_0 = \sum (p_{spot} - T)\,(E_{wind} - E_{H_2}) \tag{4}$$

Note that T is often negative, i.e. *increasing income*, since it includes both grid-access tariffs and incentives.

Up-regulating case

In the up-regulating case, we assume that the default operation of the electrolyser is just like for the reference case, but in addition the plant makes the electrolyser's power capacity available for up-regulation whenever requested by the grid.

Spot. As the contracted spot energy sales are the same as in the reference case, spot income is unchanged.

Capacity. It is assumed that the electrolyser will not be fully shut down when delivering power for up-regulation, and its power consumption will be limited by a minimum $P_{H_2}^{min} =$

0.3 MW. This assumption is justified by the unpredictable nature of hour-to-hour demand of grid services and the additional transients that a full shutdown would require. The maximum capacity that the electrolyser will be able to sell is therefore:

$$P_{cap}^{max} = \left\lfloor P_{H_2} - P_{H_2}^{min} \right\rfloor \tag{5}$$

Where the floor operator ⌊ ⌋ indicates rounding to the smallest unit of sold capacity admitted in the specific market, assumed for this study to be 1 MW.

The *actual* power capacity sold at every hour is:

$$P_{cap} = \begin{cases} P_{cap}^{max} & \text{if} \quad P_{cap}^{max} \le \left\lfloor P_{wind} - P_{H_2}^{min} \right\rfloor \\ \left\lfloor P_{wind} - P_{H_2}^{min} \right\rfloor & \text{if} \quad 0 < \left\lfloor P_{wind} - P_{H_2}^{min} \right\rfloor < P_{cap}^{max} \\ 0 & \text{if} \quad \left\lfloor P_{wind} - P_{H_2}^{min} \right\rfloor \le 0 \end{cases} \tag{6}$$

I.e. the power capacity sold on the market is the hourly power produced by the wind farm minus the minimum electrolyser consumption, bounded by 0 and by the maximum capacity that can be sold by the electrolyser itself.[1]

Income from capacity sale is proportional to P_{cap}, with a MW price for every interval:

$$I_{cap} = \sum p_{cap} P_{cap} \tag{7}$$

Activation. The actually activated reserves for the plant are proportional to the ratio of activated vs. available reserves in the market:

$$A^{\uparrow} = P_{cap} \cdot \left(\frac{A^{\uparrow}}{P_{cap}} \right)_{market} \tag{8}$$

This is the most common way to allocate activation in the faster regulation markets, as activation is determined at every capacity provider by the deviation of grid frequency from its nominal value. Italy is an exception and activates capacity sequentially, starting from the lowest bidder in the market.

Income from activation is calculated from the amount of energy exported to the grid during activation, multiplied by a price that is usually larger than or equal to the spot price:

$$I_{act}^{\uparrow} = \sum p_{act} A^{\uparrow} \tag{9}$$

Hydrogen production. While the spot income is identical to the reference case since price and volumes are set by contracts, hydrogen production is tied to the actual consumption of energy in the electrolyser, which depends on the activation of grid services: whenever up-regulation is activated, less hydrogen will be produced.

$$E_{H_2}^{\uparrow} = E_{H_2} - A^{\uparrow} \tag{10}$$

Down-regulating case

The down-regulating case is similar to the up-regulating case discussed in the previous section, with the key difference that the electrolyser is assumed to sell as much power capacity as possible while remaining barely operative.

Spot. Spot income will be higher, as less power will be diverted to the electrolyser. The nominal power for hydrogen production is now modified to set a ceiling of $P_{H_2}^{max} - P_{cap}^{max}$:

$$P_{H_2}^{\downarrow} = \begin{cases} P_{H_2}^{max} - P_{cap}^{max} & \text{if} \quad P_{H_2}^{max} - P_{cap}^{max} \le P_{wind} \\ P_{wind} & \text{if} \quad P_{H_2}^{min} < P_{wind} < P_{H_2}^{max} - P_{cap}^{max} \\ 0 & \text{if} \quad P_{wind} \le P_{H_2}^{min} \end{cases} \tag{11}$$

The income from spot sales will then be calculated with the same equation (4), only with $P_{H_2}^{\downarrow} \Delta t < E_{H_2}$.

Capacity. Capacity is calculated in the same manner as for up-regulation in equation (9). Note that that definition excludes the possibility of importing power from the grid in times of scarce wind power production: such an import would likely activate expensive power *consumer* tariffs, and besides down-regulation is less likely in times of scarce wind power production.

Activation. Activation of down-regulating reserves follows the same principle as for up-regulation (equation (8)); however, the activation price is usually *lower* or equal than the spot price, and it must be paid *by* the plant to the TSO, since the plant is taking energy off the grid. This energy had already been sold on the spot market and is now bought back at a lower or equal price, but never actually leaves the plant.

$$I_{act}^{\downarrow} = -\sum p_{act} E_{act}^{\downarrow} \tag{12}$$

Hydrogen production. In the case of down-regulation, hydrogen production is reduced at the minimum to keep the electrolyser in operation, summed with the energy from down-regulation:

$$E_{H_2}^{\downarrow} = P_{H_2}^{\downarrow} \Delta t + A^{\downarrow} \tag{13}$$

Symmetric regulating case

In some cases, capacity has to be sold on a symmetric basis, i.e. with the possibility for the TSO to request activation in either direction. In this case, the maximum capacity that can be sold on the market is:

$$P_{cap}^{max\uparrow\downarrow} = \left\lfloor \frac{P_{H_2} - P_{H_2}^{min}}{2} \right\rfloor \tag{14}$$

while income is calculated as usual per equation (7),.[2]

Nominal power for hydrogen production is calculated as per equation (11), but using $P_{cap}^{max\uparrow\downarrow}$ as ceiling.

Activation income is calculated by combining equations (9) and (12):

[1] The power capacity sold is also bound by the size of the market itself, but this limit is reached only in very small markets such as Northern Norway for large plant sizes, and even then only rarely.

[2] Note that, when using p_{cap} from TSOs operating with symmetric regulation (e.g. Norway) to extrapolate prices for single-directional capacity, we will divide these prices by two, since 1 MW of symmetric regulation actually commits 2 MW, one in each direction. Conversely, we will double single-direction capacity prices to extrapolate equivalent symmetric capacity prices (e.g. Spain).

$$I_{act}^{\uparrow\downarrow} = \sum p_{act}^{\uparrow} E_{act}^{\uparrow} - p_{act}^{\downarrow} E_{act}^{\downarrow} \tag{15}$$

Actual energy for hydrogen production is similarly calculated by adding the down-regulating energy and subtracting the up-regulating one:

$$E_{H_2}^{\uparrow\downarrow} = P_{H_2}^{\uparrow\downarrow} \Delta t + A^{\downarrow} - A^{\uparrow} \tag{16}$$

Allocation of value components

To evaluate correctly how much of the value of curtailed hydrogen is due to grid services vs. spot energy sales or subsidies on wind power, it is useful to partition it in its components. For some, the calculation is straightforward: the capacity component is simply calculated as $p_{H_2}^{cap} = I_{cap}/(H_0 - H)$, and similarly are those for incentives and tariffs.

It is however slightly more complicated to quantify the component due to capacity activation: in particular, $I_{act}^{\downarrow}$ is negative (see equation (12)), and it would appear that activation is economically detrimental. This is however intuitively incorrect, as we know that activation of down-regulating capacity involves buying back energy that was sold on the spot market at a higher price, in practice netting an income without delivering any energy. For this reason, we will split the spot income in two parts, in order to allocate it in a more sensible way.

The activation component of the value of curtailed hydrogen is therefore defined as:

$$p_{H_2}^{act} = \sum \frac{\overbrace{\left(p_{act}^{\uparrow} - p_{spot}\right)}^{\text{usually } \geq 0} A^{\uparrow} - \overbrace{\left(p_{act}^{\downarrow} - p_{spot}\right)}^{\text{usually } \leq 0} A^{\downarrow}}{H_0 - H} \tag{17}$$

whose numerator intuitively indicates the profit made by selling energy as up-activation instead of spot (first member) or by buying back energy previously sold as spot in form of down-activation. The quantity in equation (17) will be referred to as *net activation*, as opposed to the gross activation of equations (9), (12) and (15).

Including part of the spot income in the definition of $p_{H_2}^{act}$ means we must remove this part from the spot component to ensure that the overall sum p_{H_2} is still correct. We define therefore an *energy component* of the value of curtailed hydrogen defined as follows:

$$p_{H_2}^{energy} = \frac{\left(P_{H_2}^{\uparrow\downarrow} \Delta t + A^{\uparrow} - A^{\downarrow}\right) p^{spot}}{H_0 - H} = \frac{E_{H_2}^{\uparrow\downarrow} p^{spot}}{H_0 - H} \tag{18}$$

where the last passage incorporated equation (16). The energy component expresses therefore the spot price referred to the energy actually used in hydrogen production, rather than the contracted volumes given by $P_{H_2}^{\uparrow\downarrow}$.

Data sources

Data for the method presented above is collected for several countries with significantly different regimes, recapitulated in Table 1. Note that most data is provided on condition of confidentiality, and of anonymity as well for most wind parks.

Table 1 – Summary of the characteristics of the four countries considered in this study. MSD is a form of aFRR.

	Norway	France	Spain	Italy
Zone	NO4	–	–	CSUD
Service type	FCR	FCR	aFRR	MSD
Period	1 h	30 min	1 h	1 h
Capacity	✓	✓	✓	×
Activation	✓	×	✓	✓
Tariffs	✓	×	×	×
Incentives	✓	✓	×	✓

Data can often be provided cost-free by TSOs or energy exchanges, but cannot be published.

Norway

Norway's electrical energy is chiefly provided by hydro power, which represents more than 85% of electricity production [17]; as hydro power is rapidly manipulable and highly efficient, demand for grid services is limited compared to other countries, since generating plants are able to closely match their production to consumption patterns. Therefore, grid services are not as profitable in Norway as in other countries. Norway is divided into five bidding areas in the NordPool power market; we will consider area NO4 (Tromsø), which is the one where the Haeolus project's demonstration plant is located.

Two separate products are available in the Norwegian FCR capacity market, FCR-N and FCR-D: the former is a symmetrical reserve for normal operation, while FCR-D is a non-symmetrical reserve to counteract disruptive events; aFRR is not procured at all for zone NO4 [18]. In this paper, we will consider only the data of the FCR-N service, since FCR-D has negligible volumes in the NO4 zone.

Power producers in Norway must pay 13 NOK/MWh plus 7.2% of the spot price in production tariffs; in the case of wind parks, this is usually more than offset by green certificates (estimated at 116 NOK/MWh [19]) and guarantees of origin (estimated at 10 NOK/MWh [20]).

The data for the Norwegian case can be gathered from the web sites of market operator Nordpool and Norwegian TSO Statnett; the power production profile of Raggovidda was provided by Varanger Kraftvind on condition of confidentiality. All data refer to the full year of 2017. For comparison with other cases in Europe, NOK are converted to € with the average exchange rate for 2017 according to the European Central Bank, i.e. 9.327NOK/€.

Equations

The case of Norway makes use of all the equations as presented in the Methods section, with no simplifications.

France

As of January 2017, the French TSO, RTE, joined a common central European FCR procurement market with TSO's from seven other countries: Austria, Belgium, Slovenia, Switzerland, Germany, Western Denmark, and the Netherlands [21]. Bids are taken in daily auctions for 4-h symmetrical products, with a minimum bid size of 1 MW and resolutions of 1 MW. Bids given to each TSO are pooled and procured based upon a merit order list, with the settled capacity price based upon marginal pricing. Each country TSO has limitations on the amount of procured bids both within their borders and exported. In France specifically, participation in the FCR is required by all generation units which have the ability to do so, as per the French Energy Code [22] and remunerated at each half-hour in €/MW 30min. Additionally, energy activated in the FCR is also procured based upon the European Power Exchange's day-ahead spot price and balance of energy for each hour when compared to the bid capacity: if more energy is provided than the bid capacity power rating would have given, RTE will compensate the provider; if less energy is provided, the provider must compensate RTE.

FCR market data is provided on the website of RTE, including the volume capacity, capacity pricing and grid frequency. Two wind farm's power production profiles located in Bourgogne-Franche-Comté region of eastern France were used for this study. A fixed wind incentive in France of 65 €/MWh was used for simulation [23] as an average of proposed incentives in wind energy projects.

Equations

For the case of France, the equations in the Methods section are simplified so that $p_{\mathrm{spot}} = p^{\uparrow}_{\mathrm{act}} = p^{\downarrow}_{\mathrm{act}}$, which from equation (17) implies $p^{\mathrm{act}}_{\mathrm{H_2}} = 0$.

Spain

Regarding balancing services in Spain [24], i.e. FCR, aFRR, mFRR and RR, the following remuneration scheme is defined. The primary regulation, or the FCR, is a compulsory and non-remunerated service provided by the coupled generators [25]. The secondary regulation, or the aFRR, which is an optional service, is remunerated through market mechanisms both for the availability (regulation band) and for the real-time energy needs (energy provision) [26]. The tertiary regulation, or mFRR, is an optional service. If subscribed, the submission of bids for the available capacity is mandatory, both upward and downward and taking into account the availability of the primary energy source [27]. Just as in the case of the secondary regulation, tertiary regulation is remunerated through market mechanisms. RR is a voluntary service, which is also remunerated through market mechanisms.

The study carried out for Spain in this paper is focused on the aFRR services, due to its optional, automatic, and remunerated nature. This service is provided through the regulation zones[3] and its temporary action horizon ranges from 20 s to 15 min [28]. In Spain, each regulation zone has a minimum size of 200 MW and it may be composed by one or several scheduling units. Regarding availability bids submission, market participants responsible for each regulation zone may submit bids for the secondary regulation power band complying with the hourly downward/upward secondary ratio established by the TSO for the whole system. Although this ratio must be complied at regulation zone level, it is feasible that the ratio offered and allocated for each scheduling unit within the specific regulation zone is different. For the market-clearing procedure, the regulation band price shall be taken into account. The TSO shall allocate those bids that, as a whole, represent the lowest total cost overrun.

Due to the availability of wind power generation data for 2017, the regulation in force [29] and the market prices in 2017 have been used. The creation of the new European platform for the secondary regulation market, PICASSO [30], will imply changes with respect to the way in which this market is currently developed in the Spanish electricity system. In the implementation document for this platform [31], the most relevant changes can already be glimpsed, some of which are detailed below:

- Instead of the current regulation band, energy will be offered (€/MWh).
- The platform will create two lists with the bids received; one with the positive energy bids, sorted in ascending order of price, and one with the negative energy bids, sorted in descending order of price.

Equations

For the case of Spain, the equations in the Methods section are simplified so that $T = 0$, i.e. there are no incentives nor tariffs.

Italy

In Italy, FCR service is mandatory for and restricted to all the significant programmable production units with production capacity $\geq 10\,\mathrm{MVA}$ that participate in the day-ahead market [32]. Any contribution to primary regulation is considered as an unbalance and thus regulated by the corresponding legislation, which could bring penalty fees [33]. Since 2014, a voluntary remuneration scheme entered into force [34]: remuneration is energy-based and depends on the average day-ahead and dispatching services markets' prices, and its value is updated yearly by Terna [35]. Remuneration for FCR services is relatively low, also considering that costs for equipment to measure FCR are at the expense of the producer. According to current rules, a profitable market is the dispatching services market (MSD, a form of aFRR), whose legislation is under review. Until 2017, MSD was mandatory for and restricted to all the significant programmable production units participating to the day-ahead market; other units can now participate as well through pilot projects [36]. These include renewable generation, distributed generation and storage systems [37].

MSD is a pay-as-bid market where the participants bid against different scopes such as secondary regulation, minimum or switching-off, switching-on and tertiary regulation, among others. Bids are ranked in ascending order from the cheapest, accepted according to need and paid only upon activation. MSD bid quantities are set by the Italian Network Codes [32,38,39] according to specific parameters of each production unit. Production units are in turn free to decide the price of their bids for up- and down-regulation.

[3] A set of scheduling units with the capacity to regulate in response to orders from an automatic generation system, complying with the established requirements and allowing their evaluation from a real-time energy control system.

The data used for this study have been retrieved from multiple sources. Wind production refers to a real wind farm placed in the centre-south of Italy (CSUD market zone), provided under condition of confidentiality; due to a change of ownership, only data for the first ten months of 2017 were available. Market prices and quantities are provided by the Italian energy market operator [40] as XML files from their FTP server, which provides additional data not available on their website, such as public bids from the operators participating to MSD and the hours they refer to, and their corresponding activated amount. Fixed incentives of 110 €/kWh for wind power were considered [41]; this amount refers to the best possible scenario, since it is a base incentive that the renewable production units bid for in a descending price auction.

Equations

For the case of Italy, the equations in the Methods section are simplified so that $p_{cap} = 0$, as capacity is not remunerated.

Results

For all cases, wind power and market data refer to 2017. The yearly hydrogen production for both Haeolus (2.5 MW) and Raggovidda (45 MW) electrolyser sizes is reported in Table 2, together with the calculated percentage of production that is realised when operating in regime of up-, symmetric or down-regulation. Note that Italy has a lower production since the available wind power profiles are missing the last two months of 2017.

The values of curtailed hydrogen for the various countries and two electrolyser sizes are shown in Tables 3 and 4. Note that the wind power profiles used for each country have been normalised to the Raggovidda size of 45 MW.

Note that not all regimes are available in all countries (currently or in 2017): in Norway and France, bids must be symmetric; in Italy, they are set by the TSO; in Spain, they must be in both directions and proportional to the total market demands for up- and down-regulation. These results assume that the plant is free to choose one of up-, down- or symmetric regulation.

Table 2 – Yearly hydrogen production of two electrolyser sizes in connection to a wind park in several countries; wind power productions are normalised to a capacity of 45 MW. The relative production in the grid-service cases is presented as a percentage of the reference production.

[t/year]	2.5 MW (Haeolus)	45 MW (Raggovidda)
France	332.0	2003
Up	96.2%	95.4%
Symmetric	62.4%	82.5%
Down	25.5%	12.0%
Italy	246.4	1384
Up	76.7%	84.7%
Symmetric	67.6%	81.5%
Down	53.6%	30.9%
Norway	362.0	3668
Up	84.9%	82.7%
Symmetric	62.3%	65.9%
Down	38.2%	23.5%
Spain	315.5	2656
Up	83.4%	79.5%
Symmetric	63.0%	74.6%
Down	40.7%	29.7%

Table 3 – Value of curtailed hydrogen for the case of a 2.5 MW electrolyser and a 45 MW wind park in several countries, broken down in its components.

[€/kg]	Up-regulation	Symmetric regulation	Down-regulation
France			
Energy	2.27	2.28	2.29
Capacity	7.92	0.76	0.40
Incentives	3.38	3.38	3.38
Total	13.57	6.43	6.07
without incentives	10.19	3.05	2.69
Italy			
Energy	2.74	2.54	2.45
Net activation	3.32	2.75	2.27
Incentives	5.72	5.72	5.72
Total	11.79	11.00	10.45
without incentives	6.07	5.28	4.73
Norway			
Energy	1.35	1.34	1.34
Capacity	0.52	0.20	0.13
Net activation	0.08	0.03	0.02
Tariffs	−0.08	−0.08	−0.08
Incentives	0.70	0.70	0.70
Total	2.56	2.20	2.11
without incentives	1.86	1.50	1.41
Spain			
Energy	2.48	2.60	2.63
Capacity	3.44	1.50	0.96
Net activation	0.31	0.21	0.19
Total	6.23	4.32	3.78

Main trends

From Tables 3 and 4, some trends can immediately be noticed.

There are significant differences between the considered countries, with Norway standing out with particularly low values. Norway has the largest hydrogen production due to the high capacity factor of the Raggovidda wind park, but also the lowest values for curtailed hydrogen, about 2 €/kg in all cases.

The value of hydrogen curtailed for up-regulation is consistently higher than for other cases: this difference is due to the capacity component, with the exception of Italy, where capacity is not remunerated. This occurs in all countries except Norway and for both electrolyser sizes.

The presence of incentives has a dramatic effect in Italy, and to a lesser degree in France.

Finally, the values of curtailed hydrogen appear to be similar in both tables, indicating they do not strongly depend from electrolyser size.

Table 4 – Value of curtailed hydrogen for the case of a 45 MW electrolyser and a 45 MW wind park in several countries, broken down in its components.

[€/kg]	Up-regulation	Symmetric regulation	Down-regulation
France			
Energy	2.13	1.99	2.16
Capacity	8.21	2.10	0.43
Incentives	3.38	3.38	3.38
Total	13.73	7.48	5.97
without incentives	10.35	4.10	2.59
Italy			
Energy	2.62	2.38	2.40
Net activation	3.74	3.67	1.11
Incentives	5.72	5.72	5.72
Total	12.08	11.78	9.23
without incentives	6.36	6.06	3.51
Norway			
Energy	1.35	1.37	1.36
Capacity	0.49	0.26	0.11
Net activation	0.06	0.04	0.02
Tariffs	−0.08	−0.08	−0.08
Incentives	0.70	0.70	0.70
Total	2.52	2.28	2.11
without incentives	1.82	1.58	1.41
Spain			
Energy	2.51	2.62	2.66
Capacity	3.44	2.70	1.00
Net activation	0.30	0.29	0.20
Total	6.25	5.62	3.86

Discussion

The results of Tables 3 and 4 are in general encouraging as most totals, even without incentives, are higher than the EU's hydrogen price target for 2030, 1.8 €/kg [42]. In fact, for some regimes and countries, it would be profitable *already today* to accept a reduction in hydrogen production to sell grid services instead; the Clean Hydrogen Joint Undertaking gives 8 €/kg as a current baseline for end-use cost [[16], p. 150].

Differences among countries

The results indicate significant differences among the studied countries. Norway, in particular, presents consistently the lowest values for curtailed hydrogen, never passing 3 €/kg even in the most favourable conditions. While Norway is the only country among those studied levying tariffs for power generation, their effect is measured to be negligible in all cases. The combined value of capacity and net activation components varies between 50% and 10% of the energy component, which is however itself very low due to the cheap energy costs in Norway. The main reason for this disappointing performance is that Norway's power is for the most part delivered by hydro plants, which are able to ramp their production much more easily than e.g. coal or nuclear plants, and are thus able to offset variations in wind power production without external assistance. For this reason, grid services are in limited demand and are poorly paid.

France presents much more optimistic results, especially for up-regulation where the only value above 10 €/kg without incentives is achieved; this may in part be due to the reliance of France on nuclear power, which is less flexible than hydro power. However, this is also due to the fact that up-regulation would be rarely activated, and the whole capacity income is distributed over a small amount of curtailed hydrogen, less than 5% of nominal production according to Table 2. In down-regulation, the grid-service component falls to about 20% of the energy component.

Italy has promising results as well, although while France does not remunerate net activation but only capacity, Italy does the exact opposite. The net activation component is consistently in the same order of magnitude of the energy component, and often larger, with the only exception being down-regulation of the 45 MW electrolyser. Italy provided producers with very generous subsidies for wind power in 2017. These have since been reduced, but even without this income the value of curtailed hydrogen is consistently greater than 3 €/kg for all conditions.

Finally, Spain is the only considered country with no form of subsidies for wind power. Results are still positive, with a value of curtailed hydrogen in all cases above 3.7 €/kg, with a significant capacity component. The high income from capacity can be justified with the relatively high penetration of non-controllable wind power in the Spanish grid, which causes high demand for grid services.

Impact of electrolyser size

It is notable how the results of Tables 3 and 4, while being referred respectively to an electrolyser 18 times smaller than its wind park and another of the same size as the wind park, do not have radically different results. Most of the differences in the value of curtailed hydrogen can be attributed to the different production levels achieved by the two sizes in Table 2: when reducing hydrogen production, the income from capacity services is distributed on gradually more curtailed hydrogen.

The percentage reduction in hydrogen production for grid-service regimes in Table 2 refer to each size's nominal operation: it should be noted that the 45 MW size, while being 18 times larger than the smaller one, never comes close to delivering 18 times the hydrogen production in the reference case: this is because the smaller size only rarely is limited by the wind park's power output, whereas the larger one is it practically at all times, as it is by construction sized to match the park itself.

Impact of regulation mode

There are some easily identifiable patterns among regulatory regimes. In particular, the capacity component can be very large for up-regulation, contributing to remarkably high values for curtailed hydrogen: however, these high values must be multiplied for a relatively small reduction of hydrogen production, and rapidly decrease for symmetric regulation and especially down-regulation.

Implicit assumptions

One assumption that was made in the methods section was that wind power is known with reasonable accuracy one day ahead in order for the electrolyser operator to place bids on the grid-service market. Similarly, wind forecasts are necessary to bid for the spot market, and are known not to be perfectly accurate: deviations from committed production volumes can activate fines or other financial losses. Today, wind park operators (e.g. Raggovidda's Varanger Kraftvind) often outsource the forecast risk to specialised companies against a fixed share of income from power production. A similar arrangement could be set up for delivering grid services.

This is however much less important for the case of the smaller electrolyser, as it is a rare occurrence that the wind park is unable to produce enough power to meet its limited demand.

The value of curtailed hydrogen is a useful metric, but is deliberately designed around important and uncertain parameters such as electrolyser CAPEX; as such, it cannot be used to assess the overall profitability of a hydrogen plant, but only that of participation to the grid-service market of an *already* existing plant.

Comparison with literature results

As the metric proposed in this work is a novel concept, there are no direct comparisons with existing literature studies on electrolysers delivering grid-balancing services; for example, Guinot et al. [9] calculated the contribution of grid services as a fraction of LCOH, which inherently includes the capital costs of the electrolyser and other sunk costs, which our metric seeks to remove.

The study by Chardonnet et al. [12, tab. 43] is one of the few amenable to comparison; they calculate that a 1 MW electrolyser providing symmetric frequency control services in France would have a benefit of 158.5 k€/MW/year to 162.8 k€/MW/year. Using our results for France, symmetric regulation, 2.5 MW electrolyser from Tables 2 and 3, and ignoring incentives as Chardonnet et al. are not considering an electrolyser connected to a wind park, we obtain a benefit of 152.3 k€/MW/year, which is very well aligned with the reference. The slightly lower value can be due to differences in method, but is also consistent with Chardonnet et al.'s observation that per-MW revenue from grid services decreases with increasing electrolyser capacity.

Future outlook

The results indicate that grid services can improve the economy of hydrogen production plants in connection with wind parks, in some cases significantly. As the adoption of solar and wind power continues to increase worldwide thanks to decreasing costs, out-competing controllable power plants based on e.g. coal and gas, power grids will face an ever increasing need for stabilisation, and it is reasonable to expect that this demand will drive up prices for grid services, further improving the good results shown in this paper.

In countries like Norway, with a dominant hydroelectric sector that is unlikely to be replaced by wind or solar, it is not reasonable to expect such a development, and grid services will likely not be a good business proposition in the future either.

Conclusions

This paper defined a new metric to quantify the value of grid services for hydrogen production units, the value of curtailed hydrogen. Its main advantage is that it is independent from critical parameters such as the cost of the electrolyser, the market price of hydrogen or the size of the hydrogen market, which are all uncertain. Electrolysers will often have some unused capacity in a real market, and providing grid services is a viable method to monetise it.

The value of curtailed hydrogen depends on the specific market and type of regulation, whereas the size of the electrolyser seems to play a minor role. Already flexible energy systems (e.g. hydro power in Norway) have little demand for grid services, but systems with less flexible power sources offer better prospects.

The increasing uptake of solar and wind power will also stimulate demand for grid services over time, which can be met by flexible hydrogen production. Providing grid services from electrolysers can therefore support both the further deployment of renewable power sources and the critical initial phase of hydrogen production, when the market is still small and uncertain.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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