Assessing the role of green hydrogen for the system services' market in the Portuguese electricity system

Gonçalo Ramos Marques Dos Santos Costa

goncalormscosta@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

December 2021

ABSTRACT

In 2016, Portugal committed, in the Paris agreement to achieve carbon neutrality by 2050, having developed the Roadmap for Carbon Neutrality 2050 (RNC 2050), which outlines the trajectory to achieve this goal. Investments in renewable energy capacity are overseen, as well new supply and demand matching technologies, as Power-to-Gas (P2G) and Gas-to-power (G2P) using hydrogen, produced with renewable excess (green hydrogen).

However, the intense penetration of renewable energy sources introduces new challenges in the electricity sector, causing greater volatility in electricity production and possible imbalances between supply and demand. In this context, ancillary services' markets are responsible for guaranteeing a continuous supply and a good functioning of the system, although being frequently provided by fossil fuels-based power plants

Thus, the introduction of hydrogen in the market for ancillary services, in particular frequency regulation, can be seen as an asset, and a valid alternative to provide ancillary services, contributing to the objective of carbon neutrality.

This work seeks to assess the potential of green hydrogen, through P2G and G2P to provide ancillary services, for the 2050 horizon, by exploring its technical and economic viability.

The results obtained show the technical viability but display a high investment need, meaning that economically is not a viable solution, giving the current average services market price. Nevertheless, if green hydrogen P2G system can be partially funded by public investments and/or the hydrogen monetized in parallel for other end-uses, this solution can become feasible.

Key-words: Decarbonisation, green hydrogen, ancillary services market, Power-to-Gas, modelling.

1. Introduction

Renewable energies currently have a great potential to replace a very significant part of fossil fuels and therefore eliminate pollutant emissions associated with their exploration and use.

Portugal has committed to achieve the goal of total decarbonisation of the power generation sector by 2050. Solar photovoltaic and wind energy have a cost-effective potential to jointly secure 50% of the electricity generated in 2030 and 70% in 2050. However, these technologies, due to their daily variability, pose challenges in terms of security of supply. Thus, new technological solutions arise like green hydrogen production. The complementarity between electricity from renewable energy sources and green hydrogen is a good solution for Portugal on its path towards carbon neutrality. Portugal is a country that presents very favourable conditions to develop a hydrogen economy [1].

Ancillary services are characterized by being the market responsible for the safety of the electrical system. This market aims to ensure a real time balance between generation and consumption of energy, always guaranteeing the stability and reliability of the electrical system [2]. Excess renewable electricity can be converted to hydrogen, stored, and later converted back into electricity – *Power-to-Gas-to-Power* (P2G2P). In this way, hydrogen can emerge as a new energy vector for the long-term storage of excess renewables, increasing the security of supply and providing renewable energy to the grid for the periods of higher demand [1].

Thus, there is the need to assess the technical and economic viability of using green hydrogen to provide system services to the electricity grid, in the decarbonization horizon (2050).

To accomplish this goal, this work studied the potential to produce green hydrogen by Power-to-Gas (P2G), analysing how much excess of renewable energy will be available to be used in this process. It was also necessary to evaluate the dimension of the hydrogen reservoir and how much should this energy be sold to achieve a better technical and economical solution.

2. State of art

The reduction of carbon intensity in the energy sector results in significant gains in energy efficiency, providing a consequent growth of the economy and a reduction in primary and final energy consumption. Energy production and consumption will be directly associated with renewable energy sources. The aim is to greatly increase renewable capacity, in particular wind and solar energy, with the consequent reduction/abandonment of the use of fossil fuels such as coal, fuel oil and natural gas, providing a resilient, flexible, and modern system [3].

A balanced energy transition will be essential, provided by a strategy based on a combination of policies, goals, and objectives, as well as a variety of technological options, seeking to find synergies. In this perspective, hydrogen can play a key role in the decarbonization of the various sectors of the economy, particularly in the electricity sector, regarding energy storage, in a project of great incorporation of renewable sources in the final energy consumption.

The electricity sector is currently responsible for 29% of national GHG emissions, which reinforces the idea of being one of the biggest contributors to decarbonisation. On the other hand, as electrification is one of the main drivers of decarbonization of economic sectors, GHG emissions from electricity production will also indirectly play a fundamental role in the decarbonization of the economy in general, which, once again, highlights the crucial role those renewable energies will play in this context of decarbonisation. The increase in demand caused by the growing electrification of the various economic sectors will culminate in a substantial increase in renewable electricity production capacity [3]. This percentage increase in the contribution of renewable energies to the production of electricity depends essentially on the cost reduction of renewable-based technologies that has taken place in recent years, and on the cost reduction of energy storage solutions.

Solar and wind renewable energies are nowadays very competitive sources of energy, and their associated costs are increasingly being reduced. These are the two technologies where the greatest investment has been made in the past years. However, these technologies, due to their daily and inter-annual variability, pose challenges in terms of dispatchability and security of supply.

Given the characteristics of hydrogen, in particular its great potential for storing energy, it could be a very viable solution in long-term energy storage, thus having the ability to increase the dispatchability of renewables.

As it is not possible to store electricity on a national scale, the total production must equal the total consumption, to keep the frequency stable at a pre-set value, so the supply of electricity requires a balanced and effective management. The services that allow the stability of the system to be maintained are called ancillary services, they can be divided into four types: Frequency regulation, technical restriction resolution, voltage control and black start. This work will mainly focus on the frequency regulation service, which consists in the mobilization/demobilization of active power produced/consumed by the producer/consumer, maintaining the balance in the network. It is, therefore, intrinsically related to the balance between the generation and consumption of electricity, and the existence of reserves is fundamental for the system's balance to be maintained after the occurrence of disturbances in the network [2].

Frequency control generally takes place through three different types of control/reservation: The primary control starts in a few seconds and is a joint action of all generators involved. The secondary control reserve replaces the primary control (over minutes) and is activated by the responsible transmission system operator (TSOs). The tertiary control partially complements and replaces the secondary control reserve by re-scheduling generation. Like the secondary control, the tertiary control is only activated by the responsible parties/TSOs. Finally, the time control has the purpose of correcting the global time deviations of the synchronous time in the long-term as a joint action of all TSOs [4].

3. Hydrogen Production

Hydrogen is a renewable energy-carrying gas with high energy density (140 MJ/Kg), more than twice than other typical solid fuels (50MJ/Kg), and consequent potential to store energy. The world's current production of hydrogen is around 500 billion cubic centimetres per year [5]. Nowadays, about 95% of all hydrogen is generated from natural gas and coal (grey hydrogen), while only 5% is generated by electrolysis (green hydrogen).

Green hydrogen, also known as renewable hydrogen, is produced by electrolysis using renewable energy sources and with a low level of carbon consumption, 18-90 KgCO2-eq/MWh. In 2020 it presented a cost of 5.09€/Kg, while in 2030 it is expected a cost reduction to 2.12€/Kg [6] (64-74€/MWh [7]), due to the increase in productivity of wind energy. Fossil-based grey hydrogen produced by steam reforming methane (SMR) or coal gasification are considered unsustainable methods associated with emissions of 830 MtCO2 per year corresponding to 2.3% of total CO2 emissions. Hydrogen produced by SMR had a cost of 1.35€/Kg in 2020 and has an emission factor of 8.9 KgCO2/KgH2, while hydrogen produced by coal gasification has a higher emission factor of 29,339 KgCO2/KgH2 [6].

4. Methodology

To answer the research question, the problem approach was divided into three distinct steps:

1. Forecast of secondary and tertiary reservation for ancillary services, related to frequency control, for the future years of 2030, 2040 and 2050;

2. Forecast of hydrogen production capacity given excess of renewables for the future years of 2030, 2040 and 2050;

3. Modelling the hydrogen capability of offering ancillary services through *Power-to-Gas* (P2G) and *Gas-to-Power* (G2P) for the future years 2030, 2040 and 2050.

The year of 2019 was chosen has reference year for the development and validation of the proposed models. All variables were studied on an hourly basis.

4.1 Correlations between ancillary services and other parameters

Initially, we tried to find correlations between the need for ancillary services and other parameters to better predict these in a future horizon. In this sense, the following correlations were explored: Importations vs pumping; exportations vs renewable production and renewable production vs ancillary services.

4.2 Secondary regulation needs forecasting

The hourly needs for secondary regulation (upwards plus downwards), at each hour can be calculated using equation 1 [8]:

$$NRS = \beta \times \sqrt{a \times Consuption + b^2} - b \;\; [MW] \quad (1)$$

$NRS - Needs\ for\ Secundary\ Regulation,$

$a = 10\ MW, b = 150\ MW$

The consumption represents the effective consumption for each hour, and the coefficient β varies between 1.2 and 1.6 depending on the hour of the day [9].

For the year of 2019, the upward secondary regulation needs (NRSS) for each hour, were calculated by multiplying NRS with the ratio between the verified upward secondary regulation (RSSReal) and the total secondary regulation (RSReal) (equation 2). The downward secondary regulation needs (NRSD) will be the difference between NRS and NRSS (equation 3).

$$NRSS = \frac{RSSReal}{RSReal} \times NRS \;\; [MW] \qquad (2)$$

$$NRSD = NRS - NRSS \quad [MW] \qquad (3)$$

REN provides a forecast of the total annual electricity consumption for future years. The forecast consumption of each hour *h* will be estimated, multiplying the consumption verified for the same hour *h* in 2019, with ratio between the total annual consumption of the year analysed and the total annual consumption of 2019.

For the future years of 2030, 2040, and 2050 the same procedure for the secondary regulation needs was applied, although this time, for the calculation of NRSS, NRS was multiplied by the mean of ratios between the real verified upward secondary regulation and the total secondary regulation, for the set of year between 2016 and 2019.

4.3 Tertiary regulation needs forecasting

The hourly needs for the upward (NRTS) and downward (NRTD) tertiary regulations are given by equation 4 and 5 respectively [9].

$$NRTS = P + 2\% \times C + 10\% \times E \;\; [MW] \qquad (4)$$

$$NRTD = PB + 2\% \times C + 10\% \times E \ [MW] \quad (5)$$

$P - Generator\ simple\ failure, C - Consuption$

$PB - pumping\ failure, E - wind\ power$

Due to difficult in predict generator and pumping failures for each hour in future years, these variables were replaced by variation of total production between *h+1* and *h* (VP). Also, because of the big investment that has been seen for the last few years concerning solar power (S), this variable was also accounted for the forecast of tertiary regulation.

The forecast of power produced by each technology in the future was made according to the following procedures:

First the capacity factor for each technology *x* (CFx) was calculated for 2019 (equation 6):

$$CFx = \frac{Production}{Installed\ Capacity \times 365 \times 24} \quad (6)$$

Secondly, using the forecasts for the total installed capacity provided by *Direção-Geral de Energia e Geologia* (DGEG) for the years of 2030, 2040 and 2050 and assuming that, CFx calculated for 2019 will remain constant same years, we are able to calculate the total annual production for these respective years.

Thirdly, knowing the total annual production for each technology *x* for future years, the hourly production will be calculated using the same method used for the hourly consumption calculation. That is, dividing the total annual production of the technology *x* in the year *i*, for the total annual production of the same technology for the year 2019, and multiplying the result by the production registered for the same hour *h* (equation 7).

$$Production\ x_{h,i} = \frac{Annual\ Production\ x_{\ 2019}}{Annual\ Production\ x_{\ i}} \times Produção\ Bruta\ x_{h,2019} \quad (7)$$

$i = 2030, 2040, 2050$

VP is given by the difference between the total production given by all technologies at *h+1* and the total production given by all technologies at *h*.

The proposed model for forecasting tertiary regulation needs is based on the *lqnonlin Matlab* function, which solves nonlinear least squares problems (nonlinear data fitting). This parametric model obtained three coefficients (*p0, p1* and *p2*), that related the need for tertiary regulation (upwards and downwards) with the variation of the total forecasted production, the forecasted consumption, and the forecasted sum of wind and solar production respectively (equations 8 and 9).

$$NRTS = p0 \times VP + p1 \times C + p2 \times (E + S) \quad (8)$$

$$NRTD = p0 \times VP + p1 \times C + p2 \times (E + S) \quad (9)$$

4.4 Validation and results comparison with other methods

Both models' validation is based on, using the models created, estimating the needs of ancillary services for the reference year 2019 and comparing it with the secondary and tertiary regulations actually contracted in that year, through calculations of absolute error, percentage error and root mean square error (RMSE).

Two other elementary methods were created as a way of comparing the results obtained for the proposed model, "Proportion" and "Dena" methods.

"Proportion" method performs, for each year between 2013 and 2019, the quotient between the aggregate secondary/tertiary regulation and the sum between the amount of wind energy produced and the amount of solar energy produced. Then, the average of these quotients is calculated and multiply by the total amount of solar and wind energy produced for each year of 2030, 2040 and 2050. The results represent an approximation of the total needs of secondary/tertiary regulation need for the respective year.

On the other hand, the "dena" method uses the forecasts of secondary/tertiary increase between 2013 and 2030, predicted by the German energy agency *(Dena*) and apply these forecasts to the Portuguese system.

4.5 Hydrogen production forecasting

The calculation of the excess of renewable energy for the year of 2030, 2040 and 2050, is held by making the difference between the total amount of energy produced by all available technologies (equation 7), given each technology capacity factor and installed capacity evolution and the total electricity consumption for each year.

This thesis uses average efficiency values of electrolysers and fuel cells, obtained as a function of the technical specifications of each technology, with the capacity to provide P2G and G2P transformations for any amount of electricity and hydrogen [10].

- Electrolyser efficiency = 75%
- Fuel Cell efficiency = 55%

Equation 10 represents the amount of hydrogen produced by P2G and equation 11 provides the amount of electricity produced by G2P.

$$H2\ produced\ [ton] = Renewable\ Excess\ [MWh] \times P2G_{Process} \quad (10)$$

$$Energy\ [MWh] = H2\ stored\ [ton] \times G2P_{Process} \quad (11)$$

$$P2G_{Process} = \frac{3600 \times 0.75}{140 \times 1000} \left[\frac{ton}{MWh}\right]$$

$$G2P_{Process} = \frac{1000 \times 140 \times 0.55}{3600} \left[\frac{MWh}{ton}\right]$$

4.6 Model for evaluating the capacity of H2 to offer ancillary services through P2G and G2P

The final model for evaluating the ability of hydrogen to provide ancillary services consists of modelling, in *Matlab*, a balance of hydrogen production resulting from excess renewables, through the Power-to-Gas transformation. This hydrogen will be used to perform hourly offers of upward and downward secondary/tertiary energy regulation, which will be compared with the predicted needs for the years 2030, 2040 and 2050 based on the proposed models for reserve regulation forecasting. The methodology applied will be the same for each of the three years. Two dimensions of H2 reservoir were analysed.

The first step will be to define the size of the reservoir. To do this, it was verified on an hourly and weekly basis for each of the three years, what is the maximum amount of hydrogen that would be possible to produce resulting from excess renewable energy by P2G, and this same amount would be used to define the size of the green hydrogen reservoir.

For each aggregated secondary offer, 2/3 represents the upward offer and 1/3 the downward offer. In this way, the following constraints were applied to the operation:

- **1º Constrain**: Amount of hydrogen in the reservoir less than 2/3 of its maximum capacity; and,
- **2º Constrain**: Amount of hydrogen in the reservoir greater than 2/3 of its maximum capacity.

The total amounts of energy that can be offered as upward/downward secondary regulation for the hour *h+1* will be given by the following equations:

1º Constrain:

$$RSS_{h+1} = H2R_h \times G2P_{Process} \quad (12)$$

$$RSD_{h+1} = \frac{H2R_h \times G2P_{Process}}{2} = \frac{RSS_{h+1}}{2} \quad (13)$$

2º Constrain:

$$RSD_{h+1} = (ResDim - H2R_h) \times P2G_{Process} \quad (14)$$

$$RSS_{h+1} = RSD_{h+1} \times 2 \quad (15)$$

$RSS -\ Maximum\ amount\ of\ upward\ secondary\ regulation\ possible\ to\ supply,$

$RSD -\ Maximum\ amount\ of\ downward\ secondary\ regulation\ possible\ to\ supply,$

$H2R - Stored\ hydrogen,$

$ResDim - Reservoir\ Dimension.$

After the presentation of this offers to the TSO, they can be accepted or not depending on the estimated needs for secondary regulation. For both constrains, the amount of hydrogen stored is given by the equations below and depends on the acceptance of the offers and on the quantity produced by P2G from renewable excess.

1º hypothesis: Both offers are accepted:

$$H2R_{h+1,Sec} = H2R_h + P2GRen_{h+1} - \frac{NRSS_{h+1}}{G2P_{Process}} + NRSD_{h+1} \times P2G_{Process} \quad (16)$$

2º hypothesis: Only upward offer is accepted:

$$H2R_{h+1,Sec} = H2R_h + P2GRen_{h+1} - \frac{NRSS_{h+1}}{G2P_{Process}} \quad (17)$$

3º hypothesis: Only downward offer is accepted:

$$H2R_{h+1,Sec} = H2R_h + P2GRen_{h+1} + NRSD_{h+1} \times P2G_{Process} \quad (18)$$

4º hypothesis: Neither offers are accepted:

$$H2R_{h+1,Sec} = H2R_h + P2GRen_{h+1} \quad (19)$$

$H2R_{Sec} - Stored\ H2\ after\ secundary\ offers,$

$P2GRen - H2\ produced\ from\ renewable\ excess,$

$$\frac{NRSS}{G2P_{Process}}$$

$$-H2 \text{ that leaves the reservoir due to upward secundary offers } (G2P),$$

$$NRSD \times P2G_{Process}$$

$$-\ H2 \text{ that enters the reservoir due to downward secundary offers } (P2G).$$

If the new quantity of hydrogen is higher than the defined size for the reservoir, the amount of hydrogen produced by renewable excess will not be considered for the equation above.

After verifying the results of the secondary regulation market, offers will then be submitted for tertiary regulation, (equations 20 and 21):

$$RTS_{h+1} = H2R_{h+1,Sec} \times G2P_{Process} \tag{20}$$

$$RTD_{h+1} = \frac{(ResDim - \ H2R_{h+1,Sec})}{P2G_{Process}} \tag{21}$$

$$RTS - \text{ Maximum amount of upward secondary regulation possible to supply},$$

$$RTD - \text{ Maximum amount of downward secondary regulation possible to supply},$$

After the calculation of those offers, the exact same procedure and hypothesis considered for the secondary regulation, will be considered for the tertiary regulation.

1º hypothesis: Both offers are accepted:

$$H2R_{h+1,Ter} = H2R_{h+1,Sec} - \frac{NRTS_{h+1}}{G2P_{Process}} + NRTD_{h+1} \times P2G_{Process} \tag{22}$$

2º hypothesis: Only upward offer is accepted:

$$H2R_{h+1,Ter} = H2R_{h+1,Sec} - \frac{NRTS_{h+1}}{G2P_{Process}} \tag{23}$$

3º hypothesis: Only downward offer is accepted:

$$H2R_{h+1,Ter} = H2R_{h+1,Sec} + NRTD_{h+1} \times P2G_{Process} \tag{24}$$

4º hypothesis: Neither offers are accepted:

$$H2R_{h+1,Ter} = H2R_{h+1,Sec} \tag{25}$$

$$H2R_{Ter} - \text{Stored H2 after tertiary offers}.$$

5. Results analysis

5.1 *Correlations found*

All relationships investigated between renewable production and ancillary services revealed low Pearson coefficients, illustrative of negligible correlations. So, it was not possible to conclude about a concrete relationship between the frequency control ancillary services and the production of renewable energies. Consequently, it was concluded about the importance to relate ancillary services not only with the production of renewable energy, but also with other variables, which can influence the needs of reserve regulation.

There is a positive relationship between the production of renewables and exports, which leads us to conclude that the excess of renewables will used for producing green hydrogen via P2G. Concerning the analysis between energy importation and pumping, no relationship that could be considered valid was found, however, it makes sense that when consumption exceeds electricity production, this deficit will have to be compensated by pumping or energy importation.

5.2 *Validation*

Table 1 – Model Validation

	Abs Error [MWh]	Percentual Error [%]	RMSE
Sec Up	90.03	453.95	105.80
Sec Down	28.44	353.26	63.25
Ter Up	59	188.88	95.96
Ter Down	79.17	110.88	114.23

Table 1 highlights a large disparity in values between the regulation needs in 2019 calculated through the proposed models and the actual band contracted, both for the case of secondary regulation and for the tertiary regulation.

The needs for regulation obtained from the models were calculated using formulas that aim to only predict the needs for secondary and tertiary regulation required in the future. These values were compared with the data of energy regulation actually mobilized in 2019. The needs are predicted a day in advance, so there are a huge set of factors that can affect and change these forecasted values. Among these factors, the intermittence of renewable energies or momentary failures in the production/pumping of some element of the SEN stand out. It is very difficult to accurately forecast the actual value of regulation needs on the day in question, resulting in high precision errors.

Table 2 – Comparison between the forecasting models and "Proportion" and "dena" methods

GWh	*MATLAB* Model (1)	"Dena" (2)	"Propotion" (3)	Ratio 1/2	Ratio 1/3
Sec Up	1307	621	1115	2.10	1.49
Sec Down	352	68		5.19	
Ter Up	1140	1093	4226	1.04	0.74
Ter Down	1969	526		3.75	

The German power generation system is quite different from the Portuguese one, as Germany is a country with a much larger population, electricity consumption will naturally also be much higher in relation to the Portuguese consumption. On the other hand, the renewable resources existing in each country are equally different due to their geographical location. These two factors, among many others, contribute to the values observed in Table 2, when comparing the results obtained with the proposed *Matlab* models, with the ones obtained for the "dena" method.

The "proportion" method assumes the existence of a possible linear relationship between the regulation energy needs and the sum of solar and wind production. Although this method is only an elementary approximation, the quotients between the needs calculated with the proposed model and the ones obtained through the "proportion" method do not differ much from the unit value for both the total secondary regulation and the total tertiary regulation, which suggests some veracity for the values estimated by the proposed models.

5.3 Model for evaluating the capacity of H2 to offer ancillary services through P2G and G2P

Table 3 - Energy and hydrogen vector obtained with the final model – 2050

Annual values		Hourly Dimension	Weekly Dimension
Excess Renewable Available	Total [GWh]	8391	8391
	Frequency [%]	46	46
Excess Renewable Used (P2G)	Total [GWh]	3700	6676
	Fraction Used [%]	44	80
Excess Renewable Not Used (P2G)	Total [GWh]	4691	1716
	Fraction Not Used [%]	56	20
H2 Produced by Renewable Excess	Total [ton]	71363	128750
	Maximum Value [ton]	147	148

If the hydrogen that is produced by excess renewables when introduced into the reservoir, gives rise to a total stored value greater than the reservoir limit, the hydrogen in question is not produced, and therefore the excess renewables associated with its production will not be used in the market system services, but exported or used for pumping.

Logically, the larger the reservoir dimension, the greater the amount of hydrogen that can be stored and, consequently, the greater the fraction of excess renewables available, used to produce green hydrogen. All this is evidenced by Table 3, where it is possible to observe that this fraction is much higher in the weekly case, compared to the hourly case. It is also possible to observe that the greater the maximum limit of the tank, greater the amount of hydrogen produced by excess renewables.

Table 4 - Percentage of accepted regulation offers

[%]	Hourly Dimension	Weekly Dimension
Sec Up	66	95
Sec Down	60	75
Ter Up	51	68
Ter Down	45	70

Table 4 reveals a high percentage increase in the amount of offers accepted by the weekly approach relative to the hourly approach. This increase is, once again, due to a greater size of the reservoir for the weekly case. The larger the tank size, the greater the capacity and availability of hydrogen in performing ancillary service offers.

The study carried out, also shows that in none of the situations, the foreseen needs for secondary and tertiary regulation were fully satisfied, which leads to the conclusion that the P2G and G2P processes, are not sufficient by themselves to meet the expected needs of frequency control ancillary services, although in the weekly case they satisfy a large fraction of them (68-95%).

The remaining regulation energy mobilization would have to be carried out by market agents, as is happens nowadays, at times when the proposed model fails to meet such secondary and tertiary reserve needs.

5.4 Economic Analysis

Each energy production technology has a marginal cost, which represents the cost of producing an additional unit of electricity at any time. In the case of renewable technologies, which have no fuel costs and low maintenance costs, these marginal costs will be approximately null. However, for the case of fossil technologies, marginal costs are strongly associated with the price of fuel [4]. To assess the economic viability of H2 for services market, the payback was calculated, given the current services market average prices.

$$PB = \frac{I_0}{CF} \tag{26}$$

$PB - Payback\ Period,$

$I_0 - Initial\ Investment,$

$CF - Cash\ Flows$

$$Total\ Revenue = BS_{anual} \times Preço_{BS} + NRSS_{anual} \times Preço_{NRSS} + NRTS_{anual} \times Preço_{NRTS} - NRSD_{anual} \times Preço_{NRSD} - NRTD_{anual} \times Preço_{NRTD} \tag{27}$$

$BS -$ Secondary band contracted

$$CF = Total\ Revenue - Operation\ Costs - Storage\ Costs \tag{28}$$

Table 5 - Payback Period

	Hourly Dimension	Weekly Dimension
Total Revenue [M€]	96.68	146.58
Operation Costs [M€]	34.06	70.05
Storage Costs [M€]	14.91	1663
Cash Flows [M€]	47.71	1586.47
Initial Investment [M€]	18390	60054
Payback [years]	**386**	-

As it can be seen, only the hourly case presents positive cash-flows, that is, annual profit with the introduction of hydrogen vector in the resolution of ancillary services. When the sizing of the reservoir is carried out based on the maximum weekly hydrogen production value due to excess renewables, the costs associated with its storage are too high, being this the main cause for obtaining negative cash flows. This leads us to conclude that the project is not economically viable and that there are no cost-effective alternatives that allow the storage of large amounts of hydrogen.

Table 5 also reveals that the investments made are also too high, showing that both PEM electrolysers and fuel cells are technologies still under development regarding their use for P2G and G2P, to meet regulatory secondary and tertiary needs.

Too high investments result in long payback periods, far beyond the lifetime of the equipment. The proposed model presented, for the hourly case, payback periods greater than 300 years. The lifetimes of the PEM electrolyser and PEM fuel cell are around 80000 hours and 40000 hours respectively [11], which correspond to about 5 and 10 years, hence the solution proposed by the model, for the hourly case, is not an economically profitable solution as the payback period is much longer than the lifetime of the components.

The next step will then be to assess what would be the ancillary services' price using green hydrogen to obtain a payback period equal to 5 years (time after which the fuel cells need to be replaced). The downward regulation and secondary regulation prices were kept the same.

Table 6 – Upwards regulation prices using G2P

	Hourly Dimension	Weekly Dimension
Initial Investment [M€]	18390.0	60054.0
Cash Flows [M€]	3678.0	12010.8
Operation Costs [M€]	34.1	70.1
Storage Costs [M€]	14.9	1663.0
Costs of Downward Regulation (P2G) [M€]	43.1	114.1
Total Revenue of Regulation Sold (G2P) [M€]	3770.1	13858.0
Total Upward Regulation Sold [GWh]	2272.0	4378.0
Upwards regulation prices (G2P) [k€/MWh]	**1.7**	**3.2**

The final values obtained, represent extremely high prices, inconceivable to realize, which leads us once again to conclude that using hydrogen to only meet reserve regulation needs is a solution that is not economically viable for now.

6. Conclusions

The electricity-producing sector plays a fundamental role in ensuring the goal of achieving carbon neutrality by the end of 2050, mainly by the production of electricity using only renewable technologies. This results in gains in energy efficiency and provides a consequent growth in the economy and a reduction in primary and final energy consumption.

The growing penetration of renewable sources increases the importance of the ancillary services market, to restore the balance between generation and consumption and guarantee stability and security of the electrical system.

Therefore, the complementarity between the production of electricity from renewable energy sources and the production of green hydrogen could be a solution for Portugal on its path towards carbon neutrality, as it can increase the degree of dispatchability associated with renewable energy technologies through P2G and G2P transformations.

In order to assess the ability of hydrogen to provide frequency regulation ancillary services in the horizon of 2050, through the P2G and G2P processes, a model was developed to estimate the potential of green hydrogen produced by excess renewables in satisfying the needs of secondary and tertiary regulation, evaluating the technical and economic viability of this system.

The high values of error observed in Table 1 can be explained by the fact that the validation of the model was done with the amount of real energy regulation mobilized, instead of the estimated needs (which is what the model calculates).

In the implementation of the model for the 2050 horizon, it is possible to conclude about the huge excess of renewables and, therefore, a great potential for P2G, which depending on the sizing of the storage system (hourly or weekly) will have an ability to respond to the needs of ancillary services in 44-66% and 68-95% of the time respectively.

In neither the hourly and the weekly cases, the secondary and tertiary regulation were satisfied to 100%, concluding that the P2G and G2P transformations are not sufficient by themselves to respond to the totality of the system's needs.

It was also possible to conclude that this solution is not economical viable, for both cases of the storage tank dimension, given the high initial investment in electrolysers and fuel cells necessary for P2G and G2P processes.

The investments made, in each of the two cases, represent exorbitant values, which results in payback periods that are far superior to the lifetime of both the electrolysers and the fuel cells used for the project developed. Therefore, these technologies have not yet reached a stage of sufficient maturity, which allows the use of hydrogen only in the system services market.

Nevertheless, if green hydrogen P2G system can be partially funded by public investments and/or monetized in parallel for other end-uses, this solution can become viable in the future.

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