

Hydrogen and the Transition from Gas Networks to a New Energy Carrier Paradigm: Portuguese Challenges of the National Roadmap

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Abstract

Portugal has developed a national roadmap for hydrogen deployment as a key element of the Portuguese energy transition towards carbon neutrality, with a major contribution towards the electrification of society, generating synergies between the electric and gas systems. Considering the government goals for hydrogen injection within natural gas infrastructures for 2025 and 2030, as long as the indicative trajectories for 2040 and 2050, the authors used the natural gas forecast of the security of supply official report in order to obtain the hydrogen demand and power plant capacity, evaluating the system effort to meet public policy goals. Several alternative scenarios were developed for sensitive analysis, in order to assess the different strategies of hydrogen deployment, considering production from an electrolyzer. Regarding the current Portuguese situation and every scenario outcome, the authors stated that major efforts must be undertaken in order to develop full-scale hydrogen projects in order to meet the national goals.

Author Keywords. Hydrogen, Networks, Sector Coupling, Decarbonization.

Type: Research Article

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1. Introduction

The program of the Roadmap for Carbon Neutrality 2050 (RCN) and the National Energy and Climate Plan 2030 (NECP), designed by the Portuguese Government, define the national goals to achieve strong reductions of CO₂ emissions, also with the aim of guaranteeing energy sustainability of future generations, aligned with the Paris Agreement. The main goal is to enable the rational use of resources and technologies that allow the transition to a low carbon economy, enhancing endogenous resources in a cost-effective way, where hydrogen could play a significant role, up to 50% according to Fuel Cells and Hydrogen Joint Undertaking (FCH JU 2019).

The international panorama points out to a growing trend towards electrification of the economy, exploiting an energy matrix resulting from a mix of renewable sources (solar, wind, water and biofuels). Therefore, guaranteeing the carbon neutrality of national emissions, ensuring safety of supply and guaranteeing the financial sustainability of the energy system. This approach will lead also to the need of strong investments in energy transport and distribution infrastructures in order to accommodate the larger energy consumptions and renewable generation while ensuring the quality of service for consumers in a gradually complex market.

Increasing renewable energy penetration within the energy systems, along with decreasing Portuguese external energy dependency, which has been decreasing for the last 17 years (Partidário et al. 2020), require many efforts to orient public policies towards the exploitation of the electricity vector towards hydrogen production (Portuguese Government 2019). Hydrogen can be produced by either capturing surplus from the generation capacity, producing “green” hydrogen (hydrogen produced from renewable sources), either developing dedicated projects. Regarding “green” hydrogen, it can be produced by the electrolysis of water, taking advantage of the excellent potential of the renewable power resources (wind and solar) existing in Portugal. In this strategy, natural gas systems are going to integrate progressively different types of gases, in a controlled behaviour (Portuguese Government 2020a). Actually, hydrogen will allow the development of an energy sector coupling, capitalizing the surplus electricity production, which can be transformed, stored and used when necessary, assuring the energy transition of the non-domestic users where the total electrification is not cost effective (namely in intensive energy using heating industries).

The current work aims to analyse the feasibility and impacts of the Portuguese hydrogen strategy, namely considering the hydrogen injection goals into the Portuguese Gas System (PGS), assessing its impact and effort in terms of energy and power capacity, assuming production from an electrolyzer fed with surplus electricity from the system. The authors developed a sensitivity analysis regarding the thresholds given by public policies in order to accommodate uncertainty on the trajectories and evaluating the overall impact in the energy system, assuming the current energy demand forecasts from the government for the next twenty years.

2. Public Policies Review and National Strategy

The energy transition in Portugal is based on a strong electrification of the economy (Portuguese Government 2019). Portugal has enormous potential for the development of a heavily decarbonised electric power sector, by exploiting the availability of renewable endogenous resources such as hydro-electricity, wind power, solar photovoltaic (PV) and biomass. Overall, Portuguese electrical system is robust, capable of handling the time variability of renewable power sources.

Portugal’s bet in NEPC involves increasing the installed capacity of solar PV and wind power plants, fostering dedicated electricity generation projects and using the surplus of renewable energy to produce hydrogen. Highly competitive technology prices with other conventional solutions combined with the abundance of resources assures a capability of pursuing the energy transition without burdening consumers.

With a renewable based electricity system, public policies are promoting and strengthening the use of electricity in the different sectors of activity and economy, namely industry, transportation and residential and service sectors. In parallel, the decarbonization will be achieved via the exploitation of biofuels and by promoting the use of “green” hydrogen (Partidário et al. 2020). Several projections state the energy idiosyncrasy in 2050, where 24% of final energy demand can be met by hydrogen, representing 2 251 TWh in Europe (FCH JU 2019), namely:

- In electric power generation from renewable sources, assuring balancing and buffering of both networks (gas and electricity), in production surplus;
- Transportation: Heavy-duty and light-duty vehicles with fuel cell tech, also capable of transforming aviation and trains;

- Buildings: Heat and power (micro-combined heat and power) as a substitute to natural gas, coping with decentralized generation;
- Industry: Process heat needs high-temperature production, where electrification is complex, and hydrogen can achieve with blending (associated with Carbon Capture and Storage) or 100% hydrogen.

In the Portuguese National Electric System (PNES), public policies are oriented towards the decarbonization of energy production, favouring renewable sources, reducing or eliminating fossil production. However, in the PGS the challenge lies in the need to decarbonize the primary energy source, ensuring the proper compatibility of transport and distribution assets, as well as the compatibility of consumer equipment. In this context, hydrogen appears as a renewable energy carrier capable of guaranteeing not only the transformation of the PNGS but also the interaction with the PNES, ensuring the conversion of excess electrical energy into storable energy in the networks (Portuguese Government 2020a).

In the Portuguese scenario, public policies towards hydrogen development were launched in early 2020, assuring definition of strategies to decarbonize the energy systems with the complementarity of hydrogen. The final consumption is thoroughly impacted by the end usage in mobility and heating, assured also by the incorporation of green hydrogen in the gas assets, with goals of incorporation up to 40%-50% in the 2040 horizon (Portuguese Government 2020b) presented in Table 1.

Sector/Year	National Goal		Indicative trajectory	
	2025	2030	2040	2050
Natural gas network	1%-5%	10%-15%	40%-50%	75%-80%

Table 1: Hydrogen injection goals into Portuguese gas networks (NEPC, 2020)

Although the first national goals are ambitious, regarding its impact in the power system and obviously in the overall energy demand scenarios, the government also approved indicative trajectories in the 2040 and 2050 horizons. Such goals represent considerable amounts of energy within the actual context of the energy sector, but also a still long path to achieve, representing less than 5% of the overall energy consumption in 2040, as can be seen in Figure 1 (Partidário et al. 2020).

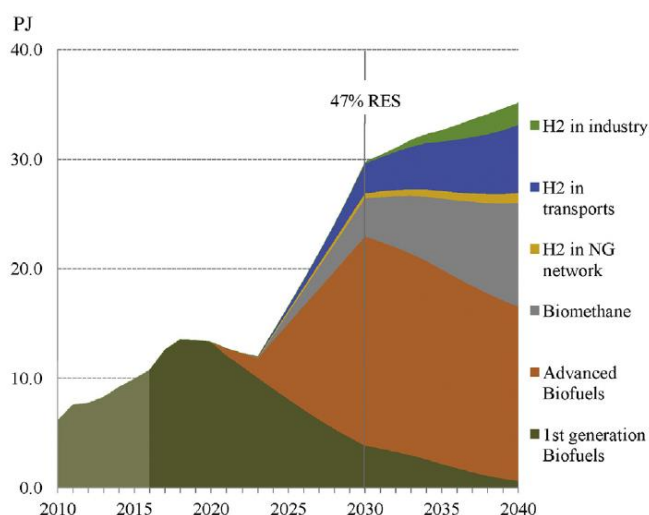


Figure 1: Renewable fuels in the frame of the 2040 47% renewable energy sources scenario

3. Transmission and Distribution Networks Capability

Currently, the European gas network consists of approximately 260 000 km of high-pressure pipelines mostly operated by transmission system operators and 1.4 million km of medium and low-pressure pipelines operated by distribution system operators (Centre for European Policy Studies 2019). Mainly the transmission and medium pressure pipelines are high quality stainless steel with inner and outer coating, and the low-pressure distribution is generally built with polyethylene pipes and accessories. Asset initial design was oriented towards methane distribution, and as one can observe, hydrogen has very distinct calorific value thresholds from methane, as long as its unique density, as reported in Figure 2, creating challenges to adapt such infrastructures, namely in high pressures (Messaoudani et al. 2016).

Properties	Hydrogen (H ₂)	Methane (CH ₄)	Unit
Molar mass	2.02	16.04	g/mole
Critical temperature	33.2	190.65	K
Critical pressure	13.15	45.4	Bar
Vapor density at normal boiling point	1.34	1.82	Kg/m ³
Vapor density (at T = 293.15 K and P = 1 bar)	0.0838	0.651	Kg/m ³
Specific heat capacity (at T = 293.15 K and P = constant)	14.4	2.21	kJ/kgK
Specific heat ratio (C _p /C _v)	1.4	1.31	—
Lower calorific value by mass (lower heating value, weight basis)	120	48	MJ/kg
Lower calorific value by volume at 1 atm	11	35	MJ/m ³
Higher calorific value by mass	142	53	MJ/kg
Higher calorific value by volume at 1 Atm	13	39	MJ/m ³
Maximum flame temperature	1800	1495	K
Explosive (deniability) limits	18.2–58.9	5.7–14	Vol % in air
Limiting oxygen for combustion	5	12	Vol %
Flammability limits	4.1–74	5.3–15	Vol % in air
Auto-ignition temperature	560	600	°C
Laminar burning velocity	3.1	0.4	m/s
Dilute gas viscosity at T = 299 K	9 × 10 ⁻⁶	11 × 10 ⁻⁶	Pa × s
Molecular diffusivity in air	6.1 × 10 ⁻⁵	1.6 × 10 ⁻⁵	m ² /s
Solubility in water	0.0016	0.025	kg/m ³

Figure 2: Hydrogen and methane physical properties, excerpt from original (Messaoudani et al. 2016)

In order to fulfil the hydrogen injection there are financial, operational, technological and regulatory challenges that the market has to gradually solve, namely:

- Financial: The network investments achieved in the last decades sum up a considerable amount of regulated assets that cannot become stranded, and, the injection framework needs capital intensive projects, not compatible with the energy production scenario nowadays (Cerniauskas et al. 2020).
- Operational: Regarding a volume analysis, hydrogen has less specific calorific value than natural gas (essentially methane) at the same pressure; therefore, for the same volume we have less energy to manage in the system, and different appliances with different compatibilities (Messaoudani et al. 2016).
- Technological: Natural gas assets are being subject to research and development for their full compatibility with a mixture up to 100% of hydrogen, because originally designed to transmit and distribute natural gas, steel pipes suffer from hydrogen embrittlement, a singularity that diminishes the strength and may cause cracking, therefore failure. On the other side, low-pressure of polyethylene has full compatibility, only raising scientific questions about the permeability rate, which increases compared to methane (Gondal 2019).
- Regulatory: The markets are designed to assure the distribution of energy to the end-users, from households up to major industries, but the regulations input caps to the gas quality (in Portugal limited to approximately 7%). With an upcoming hydrogen mixture, there are accountable differences in appliances compatibility, therefore

energy management and quality control and assurance issues to regulate (Gondal 2019).

In the Portuguese value chain scenario, the transmission network operated by REN Gasodutos, consists of several main pipelines throughout the country, totalling 1 375 km, spread over eight lots. Such pipelines have a nominal diameter ranging from 150 mm to 800 mm, constituted by stainless steel pipelines (REN 2020), which in 2019 managed 67.9 TWh of energy (of which 25 TWh into distribution gateways).

Regarding the downstream sector, there are eleven natural gas distribution networks, totalling, at the end of 2018, a network length of 18 987 km with 1.5 million customers, mainly gathered in the major cities (ERSE 2020). Six distribution networks are connected to the transmission and the remaining five are isolated, fed with local isolated solutions with liquefied natural gas. These distribution networks are mainly built of high-density polyethylene, revealing high compatibility with hydrogen (Gondal 2019), remaining some 1 000 km of steel pipelines. Therefore, such assets must be optimized in the energy future, with different renewable injection points and asymmetric usages for hydrogen, assuming different scenarios for the hydrogen roadmap deployment, throughout the upcoming decades (Marcogaz 2019):

- Phase I: The initial scenarios plan hydrogen blending within the gas infrastructure until the theoretical limit of hydrogen concentration of the gas appliances (up to 15%) (Zhao, McDonell, and Samuelsen 2019);
- Phase II: In parallel, in order to satisfy major hydrogen consumptions of particular customers, fully hydrogen networks can be developed, also with the capability of connecting with existing gas infrastructures, allowing blending of hydrogen and natural gas;
- Phase III: A final phase where the majority of the networks will distribute hydrogen and fewer branches have natural gas in order to satisfy specific customer requirements (high process heat).

Adequate planning, construction and operational management of dedicated networks could be the cost-effective solution to assure the hydrogen technical requirements for the predicted end usage scenarios, monitoring and controlling injection in different points of the natural gas existing networks (Gondal 2019). The initial development of the natural gas grids was assured with major customers and dedicated branches, with additional development of the local networks within each region (Cerniauskas et al. 2020). Therefore, such assets represent a key feature in the decarbonization strategy, in order to create a bridge between supply and distributed demand, using existing infrastructures to a faster response to public policies.

4. Methodology and Results

In order to assess the impact of the Portuguese hydrogen injection goals into gas networks, the official forecast of the Security of Supply Monitoring Report for the National Natural Gas System for the period 2019-2040 (DGEG 2019) were used in this article, approved by the government and submitted to the European commission. The General Directorate of Energy and Geology (DGEG) with the information of the Independent System Operator (REN Gasodutos) publishes the report every two years. It develops several evolutionary scenarios of gas demand in order to assess the network capacity, regarding the historical records and the economic and technical forecast information available at the time of the analysis.

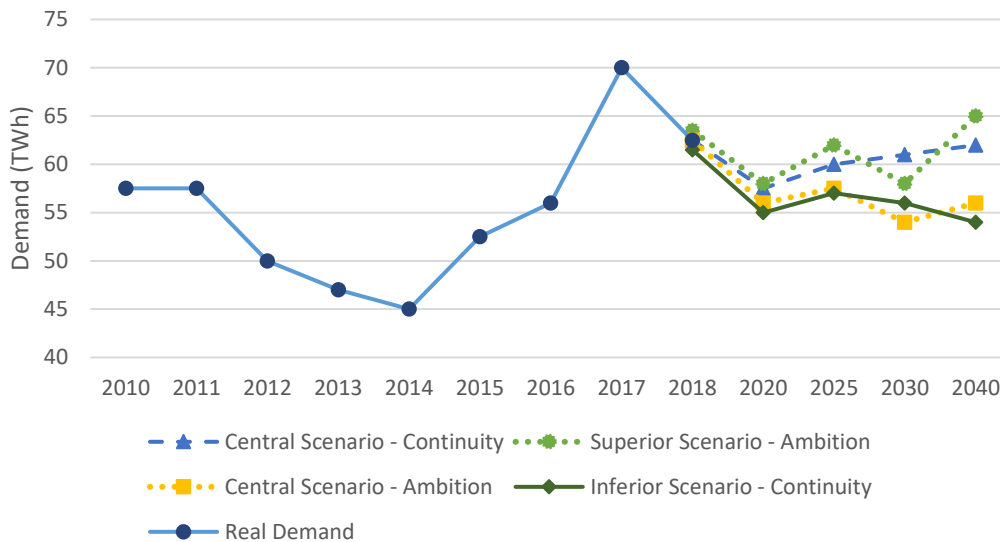


Figure 3: Gas demand forecast scenarios, DGEG (TWh)

In the latest RMSA ([DGEG 2019](#)), the gas demand forecast from 2018, [Figure 3](#), still predicted averagely a stall in the overall gas demand in the four scenarios drawn, assuming for 2040 the following targets:

- Ambition scenarios aim for 65 TWh/year;
- Pessimistic scenarios predict less than 55 TWh/year.

A relevant information regarding the RMSA analysis is the variability of the Portuguese gas consumption in combined cycles units, which is highly dependent on renewable electricity production contribution and namely on the variability of hydro contribution ([DGEG 2019](#)). Combined cycle plants overcome the periods of lack of renewables generation contributing for the supply of load during dry season replacing in this way hydro generation, which also reveals unpredictability throughout the years.

The real gas energy demand by the end of 2019 was 67.9 TWh, not predicted in RMSA at all, where only 25.4 TWh of the energy was directed to system distribution ([REN 2020](#)). The yearly forecast of RMSA is present in [Table 2](#), where the authors coded the combination of different scenarios and sector demand in order to develop further analysis, where:

- CC_n represents Central – Continuity scenario for each sector n ;
- CA_n represents Central – Ambition scenario for each sector n ;
- SA_n represents Superior – Ambition scenario for each sector n ;
- IC_n represents Central – Continuity scenario for each sector n ;
- Where $n \in \{Conventional\ Market\ (Residential,\ Tertiary,\ Industry,\ Combined\ Heat\ and\ Power);\ Electricity\ Market;\ Overall\ Gas\ Consumption\}$, $V \{1, \dots, 7\}$.

Scenario	Sector	Code	Unit	2018	2020	2025	2030	2040
Central - Continuity	Conventional market	CC1	TWh	42.8	44.1	46.1	47.7	50.9
	Residential	CC2	TWh	3.3	3.5	3.8	4.0	4.5
	Tertiary	CC3	TWh	3.4	3.6	3.9	4.1	4.6
	Industry	CC4	TWh	20.5	21.0	22.2	23.4	25.6
	CHP	CC5	TWh	15.6	16.0	16.2	16.2	16.2
	Electricity market	CC6	TWh	19.6	12.3	14.5	13.2	10.6
	Overall gas consumption	CC7	TWh	62.4	56.4	60.6	60.9	61.5
Central - Ambition	Conventional market	CA1	TWh	42.8	44.1	46.1	47.7	50.9
	Residential	CA2	TWh	3.3	3.5	3.8	4.0	4.5
	Tertiary	CA3	TWh	3.4	3.6	3.9	4.1	4.6
	Industry	CA4	TWh	20.5	21.0	22.2	23.4	25.6
	CHP	CA5	TWh	15.6	16.0	16.2	16.2	16.2
	Electricity market	CA6	TWh	19.6	12.2	12.3	6.0	5.7
	Overall gas consumption	CA7	TWh	62.4	56.3	58.4	53.7	56.6
Superior - Ambition	Conventional market	SA1	TWh	43.5	45.0	47.9	50.5	55.6
	Residential	SA2	TWh	3.3	3.5	3.9	4.2	4.8
	Tertiary	SA3	TWh	3.5	3.7	4.1	4.5	5.2
	Industry	SA4	TWh	20.5	21.2	23.0	24.9	28.7
	CHP	SA5	TWh	16.2	16.6	16.9	16.9	16.9
	Electricity market	SA6	TWh	19.6	12.6	13.5	8.3	9.2
	Overall gas consumption	SA7	TWh	63.1	57.6	61.4	58.8	64.8
Inferior - Continuity	Conventional market	IC1	TWh	42.1	43.3	44.5	45.5	46.8
	Residential	IC2	TWh	3.3	3.5	3.6	3.7	3.9
	Tertiary	IC3	TWh	3.4	3.6	3.7	3.8	3.9
	Industry	IC4	TWh	20.4	20.9	21.6	22.4	23.4
	CHP	IC5	TWh	15.0	15.3	15.6	15.6	15.6
	Electricity market	IC6	TWh	19.6	12.0	13.3	10.6	6.6
	Overall gas consumption	IC7	TWh	61.7	55.3	57.8	56.1	53.4

Table 2: RMSA gas demand forecast scenarios

Assuming the different evolution scenarios and regarding the public policies defined in the Portuguese hydrogen strategy, the methodology adopted in the current work considered the national goals thresholds, creating two scenarios:

- **High scenario:** Scenario where the public goals are achieved at its maximum impact year after year with a linearization in the yearly increase of injection of hydrogen in the gas networks.
- **Low scenario:** Scenario where the public goals are achieved at its minimum impact year after year with a linearization in the yearly increase of injection of hydrogen in the gas networks.

In order to calculate the impact of the incorporation of hydrogen within the energy demand, it was considered that the percentage of its incorporation was defined in terms of energy and not gas volume, obtaining the results in Table 3 and Table 4 for the high and low scenarios.

In [Table 3](#), one can observe that the threshold of hydrogen demand in the 2025 Low Scenario has a slight variation around 0.6 TWh.

Code	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040
CC1	TWh	0	0.09	0.18	0.27	0.37	0.46	1.32	2.18	3.05	3.91	4.77	20.36
CC2	TWh	0	0.01	0.01	0.02	0.03	0.04	0.11	0.18	0.26	0.33	0.40	1.80
CC3	TWh	0	0.01	0.01	0.02	0.03	0.04	0.11	0.19	0.26	0.34	0.41	1.84
CC4	TWh	0	0.04	0.09	0.13	0.18	0.22	0.65	1.07	1.49	1.92	2.34	10.24
CC5	TWh	0	0.03	0.06	0.10	0.13	0.16	0.45	0.75	1.04	1.33	1.62	6.48
CC6	TWh	0	0.04	0.07	0.09	0.12	0.15	0.38	0.62	0.85	1.09	1.32	4.24
CC7	TWh	0	0.12	0.25	0.37	0.49	0.61	1.70	2.80	3.90	4.99	6.09	24.60
CA1	TWh	0	0.09	0.18	0.27	0.37	0.46	1.32	2.18	3.05	3.91	4.77	20.36
CA2	TWh	0	0.01	0.01	0.02	0.03	0.04	0.11	0.18	0.26	0.33	0.40	1.80
CA3	TWh	0	0.01	0.01	0.02	0.03	0.04	0.11	0.19	0.26	0.34	0.41	1.84
CA4	TWh	0	0.04	0.09	0.13	0.18	0.22	0.65	1.07	1.49	1.92	2.34	10.24
CA5	TWh	0	0.03	0.06	0.10	0.13	0.16	0.45	0.75	1.04	1.33	1.62	6.48
CA6	TWh	0	0.04	0.06	0.08	0.10	0.12	0.22	0.31	0.41	0.50	0.60	2.28
CA7	TWh	0	0.12	0.24	0.35	0.47	0.58	1.54	2.50	3.46	4.41	5.37	22.64
SA1	TWh	0	0.09	0.19	0.28	0.38	0.48	1.39	2.31	3.22	4.14	5.05	22.24
SA2	TWh	0	0.01	0.01	0.02	0.03	0.04	0.12	0.19	0.27	0.34	0.42	1.92
SA3	TWh	0	0.01	0.02	0.02	0.03	0.04	0.12	0.20	0.29	0.37	0.45	2.08
SA4	TWh	0	0.04	0.09	0.14	0.18	0.23	0.68	1.13	1.59	2.04	2.49	11.48
SA5	TWh	0	0.03	0.07	0.10	0.13	0.17	0.47	0.78	1.08	1.39	1.69	6.76
SA6	TWh	0	0.04	0.06	0.09	0.11	0.14	0.27	0.41	0.55	0.69	0.83	3.68
SA7	TWh	0	0.13	0.25	0.37	0.49	0.61	1.67	2.72	3.77	4.83	5.88	25.92
IC1	TWh	0	0.08	0.17	0.26	0.35	0.45	1.27	2.09	2.91	3.73	4.55	18.72
IC2	TWh	0	0.01	0.01	0.02	0.03	0.04	0.10	0.17	0.24	0.30	0.37	1.56
IC3	TWh	0	0.01	0.01	0.02	0.03	0.04	0.11	0.17	0.24	0.31	0.38	1.56
IC4	TWh	0	0.04	0.08	0.13	0.17	0.22	0.62	1.03	1.43	1.84	2.24	9.36
IC5	TWh	0	0.03	0.06	0.09	0.12	0.16	0.44	0.72	1.00	1.28	1.56	6.24
IC6	TWh	0	0.04	0.06	0.09	0.11	0.13	0.32	0.50	0.69	0.87	1.06	2.64
IC7	TWh	0	0.12	0.24	0.35	0.46	0.58	1.58	2.59	3.60	4.60	5.61	21.36
% H2		0%	0.2%	0.4%	0.6%	0.8%	1.0%	2.8%	4.6%	6.4%	8.2%	10.0%	40.0%

Table 3: Evolution of renewable H2 demand in natural gas infrastructures – Low Scenario

In [Table 4](#) one can observe that the threshold of hydrogen demand in the 2025 High Scenario can vary only from 2.9 TWh up to 3.1 TWh. Comparing the different combinations of energy forecast and hydrogen development scenarios, and in the 2030 horizon, the hydrogen demands grow from 5.4 TWh, in the worst case scenario, up to 9.1 TWh. This represents more than 36% of the global gas consumption in the distribution networks, according to the latest results ([ERSE 2020](#)).

In order to assess the potential plant capacity to meet this hydrogen demand throughout the years, the present work considered that the demand was entirely met by green hydrogen technologies, namely through electrolyzers. These electrolyzers are supposed to operate with fixed capacity factor of 5 500 hours/year, and also an increasingly and linearized state of the art efficiency rate, starting from 72% in 2020 up to 82% in 2040, assuming a conservative insight from the International Energy Agency ([IEA 2015](#)).

In order to obtain an order of magnitude of the plant capacity, the power output was obtained by the classic definition of power, in [Equation 1](#), and disregarding the effects of losses within the transmission and distribution, which are less than 0.1% ([Barroso et al. 2009](#)):

$$P_{H_2} = \frac{E_{H_2}}{c \cdot \eta} [W] \tag{1}$$

Where:

- P_{H_2} represents the plant capacity, in Watt
- c represents the capacity factor in hour
- η represents the efficiency of the electrolyzer
- E_{H_2} represents the hydrogen energy demand, in Watt/hour

Code	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040
CC1	TWh	0	0.43	0.90	1.37	1.84	2.31	3.28	4.25	5.22	6.19	7.16	25.45
CC2	TWh	0	0.03	0.07	0.11	0.15	0.19	0.27	0.35	0.44	0.52	0.60	2.25
CC3	TWh	0	0.03	0.07	0.11	0.15	0.20	0.28	0.36	0.45	0.53	0.62	2.30
CC4	TWh	0	0.21	0.43	0.66	0.88	1.11	1.59	2.07	2.55	3.03	3.51	12.80
CC5	TWh	0	0.16	0.32	0.48	0.65	0.81	1.13	1.46	1.78	2.11	2.43	8.10
CC6	TWh	0	0.20	0.33	0.46	0.59	0.73	0.98	1.23	1.48	1.73	1.98	5.30
CC7	TWh	0	0.62	1.23	1.83	2.43	3.03	4.25	5.47	6.69	7.91	9.14	30.75
CA1	TWh	0	0.43	0.90	1.37	1.84	2.31	3.28	4.25	5.22	6.19	7.16	25.45
CA2	TWh	0	0.03	0.07	0.11	0.15	0.19	0.27	0.35	0.44	0.52	0.60	2.25
CA3	TWh	0	0.03	0.07	0.11	0.15	0.20	0.28	0.36	0.45	0.53	0.62	2.30
CA4	TWh	0	0.21	0.43	0.66	0.88	1.11	1.59	2.07	2.55	3.03	3.51	12.80
CA5	TWh	0	0.16	0.32	0.48	0.65	0.81	1.13	1.46	1.78	2.11	2.43	8.10
CA6	TWh	0	0.20	0.30	0.41	0.51	0.62	0.67	0.73	0.79	0.84	0.90	2.85
CA7	TWh	0	0.62	1.20	1.77	2.35	2.92	3.95	4.97	6.00	7.03	8.06	28.30
SA1	TWh	0	0.44	0.93	1.42	1.91	2.40	3.43	4.47	5.50	6.54	7.58	27.80
SA2	TWh	0	0.03	0.07	0.11	0.15	0.20	0.28	0.37	0.46	0.54	0.63	2.40
SA3	TWh	0	0.04	0.08	0.12	0.16	0.21	0.30	0.39	0.49	0.58	0.68	2.60
SA4	TWh	0	0.21	0.44	0.68	0.91	1.15	1.67	2.18	2.70	3.22	3.74	14.35
SA5	TWh	0	0.16	0.33	0.50	0.67	0.85	1.18	1.52	1.86	2.20	2.54	8.45
SA6	TWh	0	0.20	0.32	0.44	0.56	0.68	0.79	0.90	1.02	1.13	1.25	4.60
SA7	TWh	0	0.63	1.24	1.85	2.46	3.07	4.22	5.37	6.52	7.67	8.82	32.40
IC1	TWh	0	0.42	0.87	1.32	1.77	2.23	3.15	4.07	4.99	5.91	6.83	23.40
IC2	TWh	0	0.03	0.07	0.11	0.14	0.18	0.26	0.33	0.41	0.48	0.56	1.95
IC3	TWh	0	0.03	0.07	0.11	0.15	0.19	0.26	0.34	0.42	0.49	0.57	1.95
IC4	TWh	0	0.20	0.42	0.64	0.86	1.08	1.54	1.99	2.45	2.90	3.36	11.70
IC5	TWh	0	0.15	0.31	0.47	0.62	0.78	1.09	1.40	1.72	2.03	2.34	7.80
IC6	TWh	0	0.20	0.31	0.43	0.55	0.67	0.85	1.04	1.22	1.41	1.59	3.30
IC7	TWh	0	0.62	1.19	1.75	2.32	2.89	4.00	5.10	6.21	7.31	8.42	26.70
% H2		0%	1.0%	2.0%	3.0%	4.0%	5.0%	7.0%	9.0%	11.0%	13.0%	15.0%	50.0%

Table 4: Evolution of renewable H2 demand in natural gas infrastructures – High Scenario

Therefore, using Equation 1 to obtain the thresholds of the plant capacity throughout the upcoming years of the hydrogen strategy roadmap, we have obtained the following power plant capacities in Table 5 and Table 6 for both Low and High Scenarios.

Code	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040
CC1	MW	0	21.1	43.6	65.6	87.1	108.2	306.8	500.9	690.6	876.2	1057.6	4514.4
CC2	MW	0	1.6	3.5	5.4	7.2	8.9	25.6	41.9	57.9	73.4	88.7	399.1
CC3	MW	0	1.7	3.6	5.5	7.3	9.1	26.3	43.0	59.3	75.3	90.9	408.0
CC4	MW	0	10.1	21.0	31.6	42.0	52.1	149.7	245.1	338.4	429.6	518.8	2270.5
CC5	MW	0	7.7	15.5	23.2	30.7	38.0	105.2	170.9	235.0	297.8	359.2	1436.8
CC6	MW	0	9.6	16.0	22.1	28.1	34.0	88.1	141.0	192.7	243.2	292.7	940.1
CC7	MW	0	30.7	59.6	87.8	115.3	142.2	394.9	641.9	883.3	1119.4	1350.3	5454.5
CA1	MW	0	21.1	43.6	65.6	87.1	108.2	306.8	500.9	690.6	876.2	1057.6	4514.4
CA2	MW	0	1.6	3.5	5.4	7.2	8.9	25.6	41.9	57.9	73.4	88.7	399.1
CA3	MW	0	1.7	3.6	5.5	7.3	9.1	26.3	43.0	59.3	75.3	90.9	408.0
CA4	MW	0	10.1	21.0	31.6	42.0	52.1	149.7	245.1	338.4	429.6	518.8	2270.5
CA5	MW	0	7.7	15.5	23.2	30.7	38.0	105.2	170.9	235.0	297.8	359.2	1436.8
CA6	MW	0	9.6	14.6	19.5	24.2	28.9	50.6	71.9	92.8	113.1	133.0	505.5
CA7	MW	0	30.7	58.2	85.1	111.4	137.0	357.4	572.8	783.4	989.3	1190.7	5020.0
SA1	MW	0	21.4	45.0	68.0	90.4	112.4	323.1	529.0	730.4	927.2	1119.7	4931.3
SA2	MW	0	1.6	3.6	5.5	7.3	9.1	26.7	43.9	60.7	77.1	93.1	425.7
SA3	MW	0	1.7	3.8	5.8	7.7	9.6	28.5	46.9	64.9	82.5	99.8	461.2
SA4	MW	0	10.1	21.5	32.5	43.4	54.0	158.2	260.0	359.6	456.9	552.1	2545.5
SA5	MW	0	8.0	16.2	24.2	32.0	39.6	109.7	178.2	245.2	310.7	374.7	1498.9
SA6	MW	0	9.6	15.4	20.9	26.4	31.7	63.5	94.7	125.1	154.9	184.0	816.0
SA7	MW	0	31.0	60.3	88.9	116.8	144.0	386.6	623.7	855.5	1082.1	1303.8	5747.2
IC1	MW	0	20.7	42.4	63.6	84.2	104.4	293.6	478.5	659.3	836.0	1008.9	4150.8
IC2	MW	0	1.6	3.4	5.1	6.8	8.4	23.8	38.9	53.6	68.0	82.0	345.9
IC3	MW	0	1.7	3.5	5.3	7.0	8.7	24.5	39.9	55.0	69.8	84.3	345.9
IC4	MW	0	10.0	20.6	30.8	40.9	50.7	144.0	235.1	324.3	411.4	496.7	2075.4
IC5	MW	0	7.4	14.9	22.3	29.6	36.6	101.3	164.5	226.3	286.8	345.9	1383.6
IC6	MW	0	9.6	15.2	20.7	26.0	31.2	73.8	115.5	156.2	196.1	235.0	585.4
IC7	MW	0	30.4	57.6	84.2	110.2	135.6	367.4	594.0	815.5	1032.1	1243.9	4736.1
c	h	5500	5500	5500	5500	5500	5500	5500	5500	5500	5500	5500	5500
η	%	73%	74%	75%	76%	77%	78%	78%	79%	80%	81%	82%	82%

Table 5: Evolution of renewable H2 installed plant capacity – Low Scenario

Code	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040
CC1	MW	0	105.3	218.1	328.2	435.7	540.8	759.5	973.3	1182.3	1386.6	1586.5	5643.0
CC2	MW	0	8.1	17.6	26.8	35.8	44.6	63.1	81.2	98.8	116.1	133.0	498.9
CC3	MW	0	8.4	18.0	27.5	36.7	45.7	64.7	83.2	101.3	119.0	136.4	510.0
CC4	MW	0	50.4	104.8	157.9	209.8	260.4	368.7	474.6	578.1	679.3	778.3	2838.1
CC5	MW	0	38.4	77.7	116.0	153.5	190.0	263.0	334.3	404.0	472.1	538.8	1796.0
CC6	MW	0	48.2	79.8	110.6	140.7	170.1	226.3	281.3	335.1	387.6	439.0	1175.2
CC7	MW	0	153.5	297.9	438.8	576.4	710.9	985.9	1254.6	1517.3	1774.2	2025.5	6818.2
CA1	MW	0	105.3	218.1	328.2	435.7	540.8	759.5	973.3	1182.3	1386.6	1586.5	5643.0
CA2	MW	0	8.1	17.6	26.8	35.8	44.6	63.1	81.2	98.8	116.1	133.0	498.9
CA3	MW	0	8.4	18.0	27.5	36.7	45.7	64.7	83.2	101.3	119.0	136.4	510.0
CA4	MW	0	50.4	104.8	157.9	209.8	260.4	368.7	474.6	578.1	679.3	778.3	2838.1
CA5	MW	0	38.4	77.7	116.0	153.5	190.0	263.0	334.3	404.0	472.1	538.8	1796.0
CA6	MW	0	48.2	73.1	97.4	121.1	144.3	155.8	167.1	178.2	189.0	199.6	631.9
CA7	MW	0	153.5	291.2	425.6	556.8	685.0	915.4	1140.4	1360.5	1575.6	1786.0	6274.9
SA1	MW	0	107.0	224.8	339.9	452.2	561.9	795.7	1024.2	1247.6	1466.0	1679.6	6164.1
SA2	MW	0	8.1	17.9	27.4	36.7	45.7	65.4	84.6	103.4	121.7	139.7	532.2
SA3	MW	0	8.6	18.8	28.8	38.6	48.1	69.3	90.1	110.4	130.3	149.7	576.5
SA4	MW	0	50.4	107.3	162.7	216.9	269.8	386.6	500.7	612.3	721.4	828.2	3181.8
SA5	MW	0	39.9	80.9	120.9	160.0	198.2	274.4	348.7	421.4	492.5	562.1	1873.6
SA6	MW	0	48.2	76.8	104.6	131.8	158.4	183.0	207.0	230.6	253.6	276.1	1020.0
SA7	MW	0	155.2	301.6	444.5	584.0	720.2	978.7	1231.2	1478.1	1719.5	1955.7	7184.0
IC1	MW	0	103.6	212.0	317.8	421.1	522.0	729.4	932.0	1130.1	1323.8	1513.3	5188.5
IC2	MW	0	8.1	17.0	25.6	34.0	42.2	59.1	75.7	91.8	107.6	123.1	432.4
IC3	MW	0	8.4	17.4	26.3	35.0	43.4	60.8	77.7	94.3	110.5	126.4	432.4
IC4	MW	0	50.2	102.8	154.2	204.4	253.4	356.2	456.7	555.0	651.0	745.0	2594.2
IC5	MW	0	36.9	74.7	111.7	147.8	183.0	253.2	321.9	389.0	454.7	518.8	1729.5
IC6	MW	0	48.2	76.1	103.4	130.0	156.0	197.1	237.3	276.6	315.0	352.5	731.7
IC7	MW	0	151.8	288.1	421.2	551.1	678.0	926.5	1169.3	1406.7	1638.8	1865.9	5920.2
c	h	5500	5500	5500	5500	5500	5500	5500	5500	5500	5500	5500	5500
η	%	73%	74%	75%	76%	77%	78%	78%	79%	80%	81%	82%	82%

Table 6: Evolution of renewable H2 installed plant capacity – High Scenario

In Table 7 and Table 8, authors summarize the energies and the electrolyzer power plant capacities for the different scenarios. One can observe that the hydrogen plant capacity in the 2025 scenario can range from 406.8 MW up to 432.1 MW, comparing the different combinations of energy forecasts and hydrogen development scenarios. For the 2030 horizon, the power capacity grows from 1 488 MW in the worst-case scenario up to 1 689 MW.

Scenario RMSA	Scenario H2 Policy	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040
CC	High	GW	0,00	0,15	0,30	0,44	0,58	0,71	0,99	1,25	1,52	1,77	2,03	6,82
	Average	GW	0,00	0,09	0,18	0,26	0,35	0,43	0,69	0,95	1,20	1,45	1,69	6,14
	Low	GW	0,00	0,03	0,06	0,09	0,12	0,14	0,39	0,64	0,88	1,12	1,35	5,45
CA	High	GW	0,00	0,15	0,29	0,43	0,56	0,69	0,92	1,14	1,36	1,58	1,79	6,27
	Average	GW	0,00	0,00	0,17	0,26	0,33	0,41	0,64	0,86	1,07	1,28	1,49	5,65
	Low	GW	0,00	0,03	0,06	0,09	0,11	0,14	0,36	0,57	0,78	0,99	1,19	5,02
SA	High	GW	0,00	0,16	0,30	0,44	0,58	0,72	0,98	1,23	1,48	1,72	1,96	7,18
	Average	GW	0,00	0,00	0,18	0,27	0,35	0,43	0,68	0,93	1,17	1,40	1,63	6,47
	Low	GW	0,00	0,03	0,06	0,09	0,12	0,14	0,39	0,62	0,86	1,08	1,30	5,75
IC	High	GW	0,00	0,15	0,29	0,42	0,55	0,68	0,93	1,17	1,41	1,64	1,87	5,92
	Average	GW	0,00	0,00	0,17	0,25	0,33	0,41	0,65	0,88	1,11	1,34	1,55	5,33
	Low	GW	0,00	0,03	0,06	0,08	0,11	0,14	0,37	0,59	0,82	1,03	1,24	4,74

Table 7: Evolution of renewable H2 installed plant capacity - Comparison between scenarios

Scenario RMSA	Scenario H2 Policy	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040
CC	High	TWh	0,0	0,6	1,2	1,8	2,4	3,0	4,3	5,5	6,7	7,9	9,1	30,8
	Average	TWh	0,0	0,4	0,7	1,1	1,5	1,8	3,0	4,1	5,3	6,5	7,6	27,7
	Low	TWh	0,0	0,1	0,2	0,4	0,5	0,6	1,7	2,8	3,9	5,0	6,1	24,6
CA	High	TWh	0,0	0,6	1,2	1,8	2,3	2,9	3,9	5,0	6,0	7,0	8,1	28,3
	Average	TWh	0,0	0,4	0,7	1,1	1,4	1,8	2,7	3,7	4,7	5,7	6,7	25,5
	Low	TWh	0,0	0,1	0,2	0,4	0,5	0,6	1,5	2,5	3,5	4,4	5,4	22,6
SA	High	TWh	0,0	0,6	1,2	1,9	2,5	3,1	4,2	5,4	6,5	7,7	8,8	32,4
	Average	TWh	0,0	0,4	0,7	1,1	1,5	1,8	2,9	4,0	5,1	6,2	7,4	29,2
	Low	TWh	0,0	0,1	0,2	0,4	0,5	0,6	1,7	2,7	3,8	4,8	5,9	25,9
IC	High	TWh	0,0	0,6	1,2	1,8	2,3	2,9	4,0	5,1	6,2	7,3	8,4	26,7
	Average	TWh	0,0	0,4	0,7	1,1	1,4	1,7	2,8	3,8	4,9	6,0	7,0	24,0
	Low	TWh	0,0	0,1	0,2	0,4	0,5	0,6	1,6	2,6	3,6	4,6	5,6	21,4

Table 8: Evolution of renewable H2 demand in natural gas infrastructures - Comparison between scenarios

Considering the information of the previous tables, one can observe that in every scenario of the hydrogen deployment policy, and regarding the RMSA scenarios, Portugal has to be capable to generate, in average, approximately two TWh of hydrogen by 2025, with an average installed capacity in electrolyzers of 400 MW. This plant capacity demand represents almost forty times the largest electrolyzer in terms of scale up of today’s units (FCH JU 2018). The current results demonstrate that the variability between the scenarios is considerable in terms of hydrogen demand and obviously in terms of plant capacity.

5. Conclusions

The injection of increasing quantities of hydrogen in the PGS represents a clear response of the energy policy aiming at the carbon neutrality goals, representing the capacity to transform the energy system, by increasing security of supply, fostering synergies between the electric and the natural gas system, while ensuring a decrease in imports of primary fossil energy.

The results of this paper show that there is a sense of urgency in the development of full-scale hydrogen injection projects in order to assure the energy transition goals for the next upcoming years.

The PGS regulated assets have a considerable life expectancy and can deliver an essential role in decarbonizing the energy system, requiring investments to replace some sections, namely pipelines whose compatibility is reduced (carbon steel), and this way avoiding stranded assets in the upcoming years.

Long-term planning of the transport and distribution hydrogen network must be evaluated in order to develop dedicated hydrogen networks, fostering the energy transition of key customers, and assuring a fair transition of the current customer base of natural gas.

Portuguese current hydrogen goals of 2025/2030 and the indicative trajectories of 2040/2050, considering the status of such inexistence of hydrogen injection, imply a major effort to meet either the most conservative deployment scenarios or even the most ambitious ones.

The Portuguese energy policies, namely the hydrogen roadmap towards 2050, set national goals of hydrogen use, such as injection targets in gas infrastructures, which imply considerable efforts of investment and planning to meet the several objectives of hydrogen incorporation within the energy system.

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