

Review

An Overview of the Portuguese Energy Sector and Perspectives for Power-to-Gas Implementation

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Abstract: Energy policies established in 2005 have made Portugal one of the top renewable power producers in Europe, in relative terms. Indeed, the country energy dependence decreased since 2005, although remaining above EU-19 and EU-28 countries in 2015 (77.4% vs. 62.4% vs. 54.0%, respectively). Data collected from governmental, statistical, and companies' reports and research articles shows that renewables and natural gas assumed a growing importance in the Portuguese energy mix along time, while oil followed an opposite trend. Recently, the country remarkably achieved a full 70-h period in which the mainland power consumed relied exclusively on renewable electricity and has several moments where power production exceeds demand. Currently, the main option for storing those surpluses relies on pumped hydro storage plants or exportation, while other storage alternatives, like Power-to-Gas (PtG), are not under deep debate, eventually due to a lack of information and awareness. Hence, this work aims to provide an overview of the Portuguese energy sector in the 2005–2015 decade, highlighting the country's effort towards renewable energy deployment that, together with geographic advantages, upholds PtG as a promising alternative for storing the country's renewable electricity surpluses.

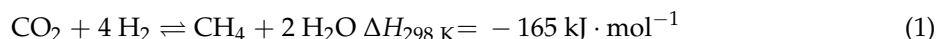
Keywords: CO₂ capture and utilization; energy dependence; power-to-methane; synthetic natural gas; renewable power; fossil fuels

1. Introduction

The Renewable Energy Roadmap 21 settles for 2020 and for the whole European Union a share of energy from renewable sources of 20% [1]. Some countries, such as Portugal, have already reached or surpassed such a target [2,3]; in fact, the current energy situation in the country has significantly changed in the last decade, when renewable energy deployment strategies were still under debate [4]. Portugal was the fourth country of the European Union with a higher incorporation of renewable electricity in 2015 (44.6%) after Denmark (50.2%), Austria (62.6%), and Sweden (72.1%) [3]. The Portuguese renewable annual electricity production has increased almost fourfold since 2005 and reached 33.3 TWh in 2016, relying mostly on hydro (16.9 TWh) and wind (12.5 TWh) sources, together representing 88% of the total renewable power production [3].

In Portugal, an annual surplus of renewable power production in the range of 800–1200 GWh is estimated for 2020 [5,6]. As renewable power relevance increases within the energy sector, developing a way to efficiently and economically store its surpluses in periods of low demand becomes an urgent problem to be tackled [7]. Among the systems available or under development for such a purpose (pumped hydroelectric storage, compressed air energy storage, electrochemical and flow batteries) [8], power-to-gas technologies (PtG) are receiving increased attention, particularly in Europe [9–11], and a storage potential of at least 500 GWh has been foreseen in Portugal [6]. One PtG option could be to

use the surplus electricity for H₂O electrolysis to obtain H₂ (PtH), but its storage remains a challenge and lacks a dedicated infrastructure for its distribution [2]. Another way is to use that “green” H₂ and blend it in natural gas, but only up to 10% without major effect in the gas grid and end-use equipment, or further convert it to methane (PtM), also called substitute/synthetic natural gas (SNG), through the Sabatier reaction (Equation (1)) [9]. Methane is far simpler to store and transport than pure H₂ using the well-established natural gas infrastructure and therefore enabling the connection between the power and natural gas grids [12,13].



Synthetic natural gas can be later reconverted to electricity in periods of high demand or used as feedstock or fuel. Thus, SNG can be seen as a secure and efficient supply of renewable energy, while simultaneously reducing the dependence on (imported) fossil fuels and supporting the transition towards a low-carbon economy [14–16].

Bailera et al. [10] reported the existence of 43 PtG projects worldwide taking place in 11 countries, with most initiatives occurring in Germany (16 projects), Denmark (7 projects), and Switzerland (6 projects) as a result of strong governmental support. In the review by Quarton and Samsatli [13], these results were updated, with Germany standing out among other countries with 45 projects, either finished, planned, operating, or under construction. The main drivers towards PtG in Germany are the existence of geographic advantages for PtG implementation, like the availability of enough suitable underground gas storage capacity and a sufficient gas network development for gas distribution [11,17], as well as the country targets to increase its power generation with origin in renewable sources from 32% (in 2015) to 50% and 80% in 2030 and 2050, respectively [18]. In Portugal, despite being a pioneering country regarding the adoption and massive diffusion of wind power parks across its territory, the first national research project in the country dedicated to the topic was launched in mid-2018 [19], dealing with the development of a cyclic sorption-reaction process for simultaneous CO₂ capture and conversion to methane to be coupled in PtG applications (cf. Figure 1).

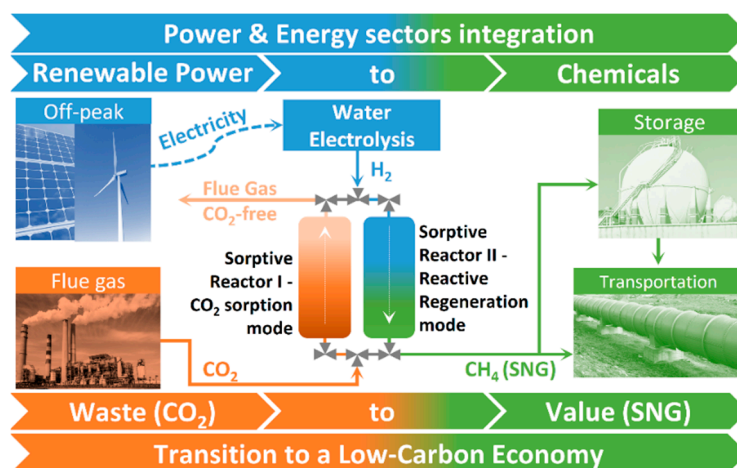


Figure 1. Power-to-gas concept: system boundaries with a cyclic sorption-reaction process for CO₂ capture and conversion/utilization. Reprinted from Chemical Engineering Journal, 322, C.V. Miguel, M.A. Soria, A. Mendes, L.M. Madeira, A sorptive reactor for CO₂ capture and conversion to renewable methane, 590–602, Copyright (2017), with permission from Elsevier.

There are few studies concerning the assessment of power-to-gas implementation potential in Portugal. The first work was by Heymann and Bessa [6], who estimated the cost of PtG products in the country as a function of the distance to wind power parks and gas storage facilities. The levelized cost of energy when considering SNG as a final product ranged between 0.05–0.10 €/kWh. Recently,

Carneiro et al. [20] presented the opportunities for large-scale energy storage in geological formations in mainland Portugal.

While PtG demonstration activities are growing fast, particularly in Europe, the current situation in Portugal supports the findings by Bento and Fontes [21] that, typically, Portugal has an average adoption of energy-related technologies lag of one to two decades relative to “core” countries (i.e., energy technology developers/leaders, generally from the OECD-Organization for Economic Co-operation and Development) [21]. Hence, the present work aims to contribute to the current state-of-art by providing a background image of the Portuguese energy sector (Section 2), presenting the main facts and figures, such as the country energy dependence evolution with time (Section 2.1), the consumption of fossil fuels (Section 2.2), and renewable power production (Section 2.3). Afterwards, in Section 3, requirements for power-to-gas implementation are described, namely the availability of renewable power surpluses (Section 3.1), carbon dioxide sources for the methanation (Section 3.2), and access to the natural gas grid for SNG storage and distribution (Section 3.3). In Section 3.4, needs for future research are identified and, finally, in Section 4, the main conclusions and the most important steps that all interested parties should take to raise awareness regarding deployment of PtG in Portugal are presented. Figure 2 shows a diagram presenting the approach adopted in this work.

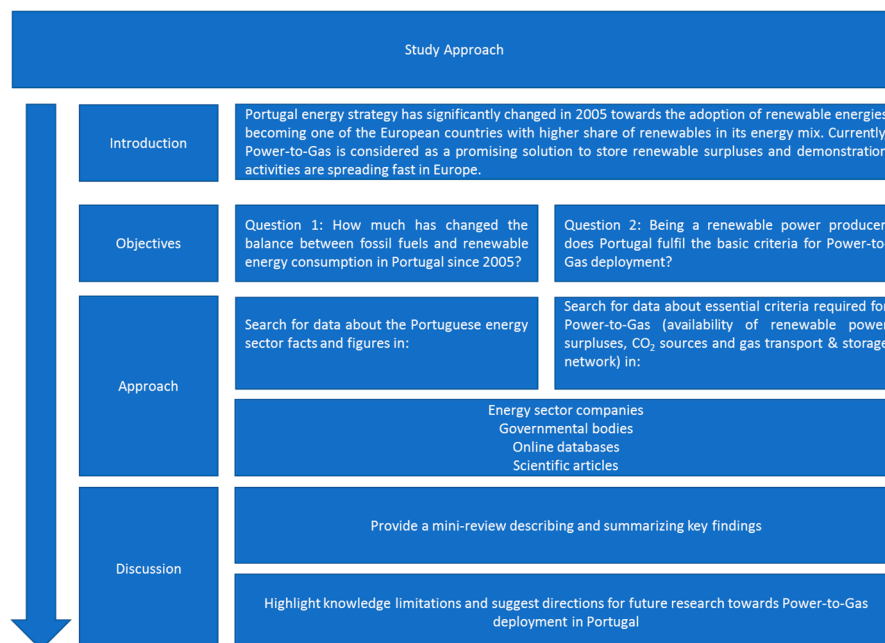


Figure 2. Diagram presenting the study approach adopted in this work.

2. Overview of the Portuguese Energy Sector

2.1. Energy Dependence

The energy dependence (*ED*) is a parameter that characterizes the extent to which an economy relies upon imports to meet its energy needs. The indicator is calculated as net imports of primary energy (i.e., (*IMP*) importations minus exportations (*EXP*)) divided by the sum of gross inland energy consumption (*GIC*) plus international maritime bunkers (*IMB*) (cf. Equation (2)) [22].

$$ED(\%) = \frac{IMP - EXP}{GIC + IMB} \times 100 \quad (2)$$

The Portuguese energy dependence and the dependence of the Euro-economic area (EU-19) and European Union countries (EU-28) are shown in Figure 3 for comparison.

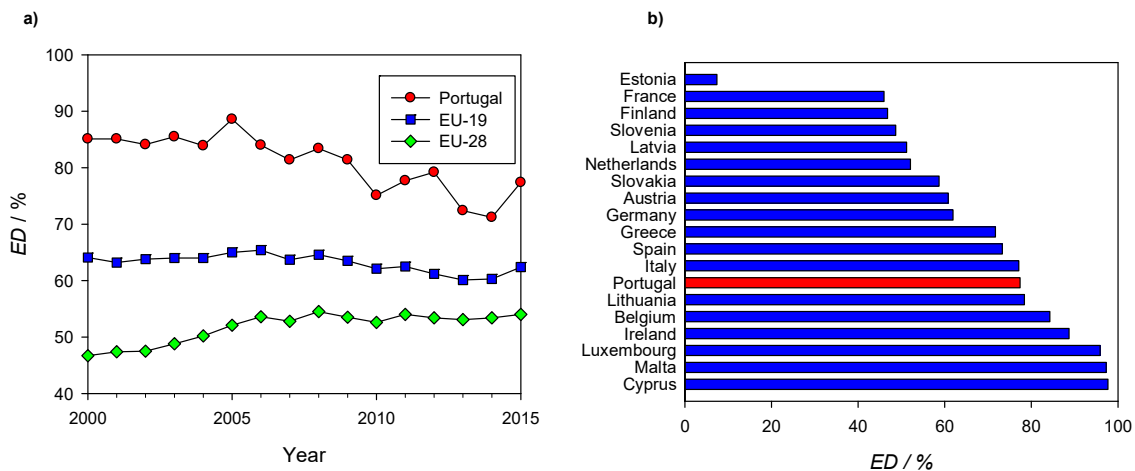


Figure 3. Portuguese energy dependence (ED): (a) Along recent years and (b) comparison with EU-19 countries in 2015. Data taken from Eurostat online database [22].

Portugal had the seventh highest energy dependence among the EU-19 and EU-28 countries in 2015 (cf. Figure 3b). None of the EU-19 countries had a negative energy dependence (cf. Figure 3b), all depending on primary energy imports to satisfy their energetic needs.

The normalized consumption of primary energy (CPE) per type of source in Portugal is shown in Figure 4a, for the period of 2000–2015. The country situation is compared with those from EU-19 and EU-28 group countries for the year, 2015, in Figure 4b.

The National Energy Strategy, approved in 2005 by the Portuguese Government, settled strategic policies, such as the energy market liberalization, the promotion of energy from renewable sources, and of technologies with improved efficiencies [23]. As a result, the oil share remarkably declined (i.e., 14.6%) in the following decade, replaced by natural gas and energy from renewable sources, whose values increased by 4% and 9%, respectively, while the coal share practically remained constant in the same period (a rise of only 1.6%) (cf. Figure 4a). Still, fossil fuels represented 78% of the consumed primary energy in 2015, a value slightly above EU-19 (72%) and EU-28 (73%) group countries, whose patterns are nearly identical (cf. Figure 4b). The remaining primary energy was exclusively based on renewable sources (22%), making Portugal the fifth country with the highest share of energy from renewables amongst the EU-28 countries [24]. The weight of renewables becomes more significant when considering primary energy consumption exclusively for power production purposes. In fact, 45% of the electricity produced in 2015 was obtained from renewable sources [3]. Nuclear has almost the same weight as the energy from renewable sources (ca. 13–15%) in EU-19 and EU-28 groups, although it is absent in some members, like Portugal.

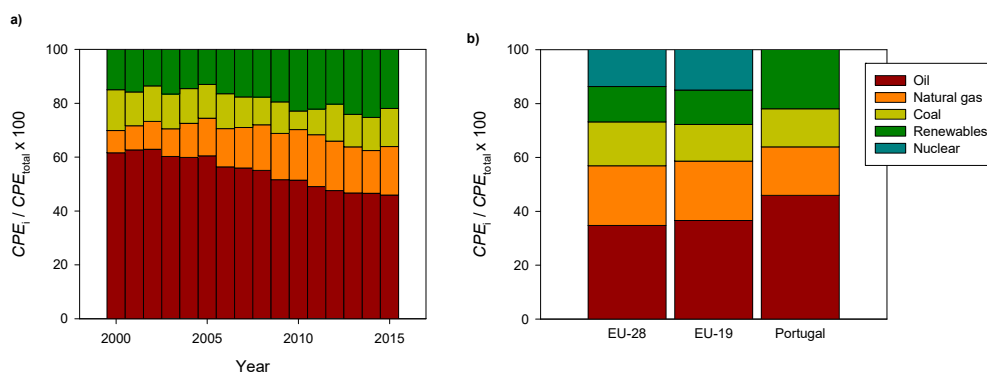


Figure 4. Normalized primary energy consumption per type of source in Portugal: (a) From 2000 to 2015 and (b) comparison with EU groups in 2015. Authors calculations based on data taken from Eurostat online database [22] and excluding the negligible contribution of non-renewable waste sources.

The last 10 years up to the present regarding fossil fuels and energy from renewable sources contributions to the Portuguese energy sector is presented in Sections 2.2 and 2.3, respectively, with an emphasis on renewable power production, as it is one of the main building blocks of power-to-gas technologies.

2.2. Energy from Fossil Fuels

2.2.1. Oil

Up to now, Portugal does not have indigenous oil reserves with economic viability, although regular onshore and offshore exploration activities have been carried out since 1940. Therefore, all oil consumed by the country is imported. Table 1 lists the top five supplier countries from 2014 to 2016. In the listed years, Portugal imported oil from 13–15 countries and the top five oil suppliers were responsible for around 66–76% of the total imported oil. Angola was the major oil supplier with a contribution of ca. 25%. Diversification of oil suppliers along the years has contributed to assure reliable and secure access to fossil energy resources [25].

Table 1. Top five oil suppliers to Portugal and their corresponding share (based on data taken from [26]).

Top-5	2014	2015	2016
1st	Angola (26.1%)	Angola (22.9%)	Angola (24.9%)
2nd	Saudi Arabia (12.6%)	Saudi Arabia (14.2%)	Russia (19.7%)
3rd	Algeria (9.9%)	Kazakhstan (10.6%)	Azerbaijan (11.1%)
4th	Kazakhstan (9.7%)	Algeria (9.5%)	Saudi Arabia (10.8%)
5th	Azerbaijan (9.2%)	Azerbaijan (9.0%)	Kazakhstan (9.3%)
Imp. oil (10⁶ ton)	7.5 (out of 11.17)	9.1 (out of 13.73)	10.7 (out of 14.09)
Nr. oil suppliers	14	15	13

Figure 5 shows the final consumption of oil by activity sector. The transportation sector is responsible for the largest share (ca. 75–79%). Oil consumption declined in all sectors for the five year period, except Agriculture/Forestry, which remained practically constant. Within the Portuguese industry sector, the non-metallic minerals industries (e.g., cement and glass) were by far the activities with higher oil consumption (i.e., 50–60% of the oil consumed by the industry sector).

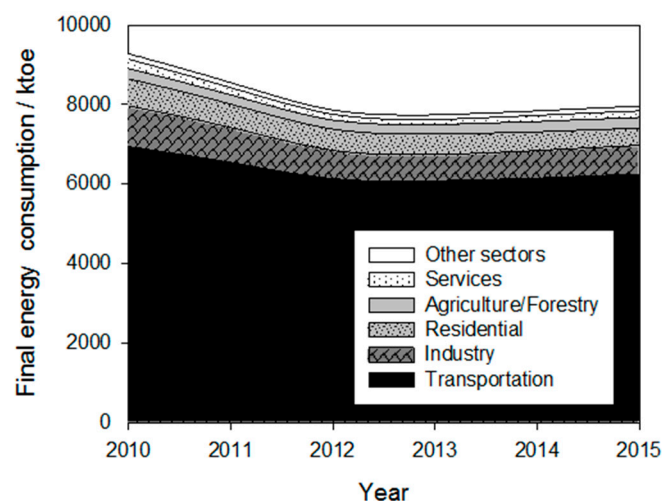


Figure 5. Evolution of oil products' final energy consumption in Portugal by activity sector from 2010 to 2015 (data taken from [27]).

2.2.2. Coal

After national coal production ceased in 1994, Portugal dependence on imported coal to secure its energy needs increased. Portugal imported 4.5 millions of tonnes of coal from Colombia (88.1%),

the United States (6.6%), South Africa (3.5%), and Ukraine (1.8%) in 2014 [24]. Imported coal is of the bituminous type, being used essentially for electricity generation in two coal-fired power plants located in Sines (1250 MW) and Pego (620 MW). These plants act as a backup system, guaranteeing that power demand is fulfilled in periods of low renewable power production. Coal consumption is particularly dependent on the hydrological conditions, namely when hydropower output is lower during drought periods. Coal is also consumed by end-users from the industry sector, namely by the iron and steel industries, in chemical/petrochemical plants, and by the non-metallic minerals industries (cf. Figure 6). Nevertheless, the amount of coal used by these end-users is negligible when compared to the quantity used for electricity production (e.g., 12 ktce vs. 3246 ktce, respectively). Still, coal consumption by the non-metallic minerals and chemical sectors has decreased considerably from 2010 to 2015 (cf. Figure 6). The amount of coal consumed in 2014 and 2015 by the non-metallic minerals, iron and steel, and chemical/petrochemical sub-sectors was similar (ca. 4 ktce/each) (Figure 6).

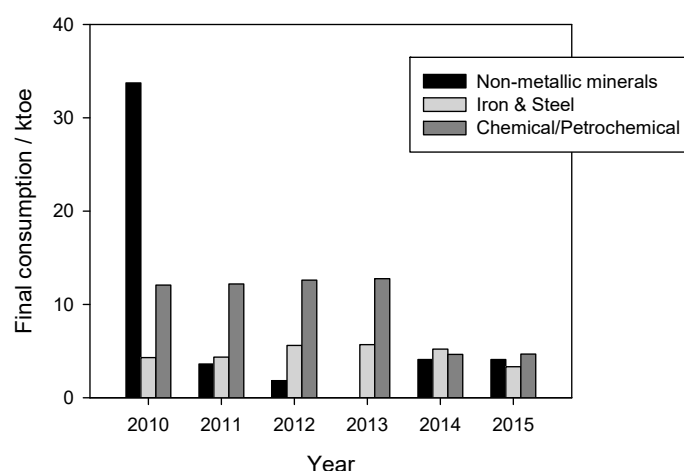


Figure 6. Coal consumption by the industry sub-sectors from 2010 to 2015 [27].

2.2.3. Natural Gas

Portugal has no natural gas resources. Table 2 shows natural gas import origins and corresponding volumes for the years, 2014 and 2015.

Table 2. Natural gas imports (10^6 m^3) in the years 2014 and 2015 [28].

Delivery Type	Origin	2014	2015
Pipeline (Natural gas)		2736	3002
	Algeria	2196	2111
	Spain	535	891
	Not specified	5	0
Ships (Liquefied natural gas-LNG)		1523	1776
	Algeria	102	210
	Qatar	687	224
	Nigeria	352	1166
	Norway	80	80
	Spain ¹	6	7
	Trinidad and Tobago	223	89
	Not specified	73	0
TOTAL		4259	4778

¹ LNG imported using tanker trucks.

Around 64% of the supplies were received through a pipeline, while the remaining part, liquefied, was transported to Portugal in ships that unload at the Sines terminal, on the southern part of the country. Only a negligible quantity ($6\text{--}7 \times 10^6 \text{ m}^3$) was imported using tanker trucks exclusively from Spain. The most important supplier is Algeria, with a share ranging between 45–52%, while Qatar and Nigeria were the major suppliers of liquefied natural gas (LNG).

The final energy consumption of natural gas by activity sector is shown in Figure 7. The industry sector accounts for the largest amount of natural gas consumption (67–74%), followed by the residential (16–19%) and services (13–14%) sectors. The use of natural gas in the agriculture/forest and transportation sectors is negligible and both sectors represent only ca. 1% of the total consumption. Energy for transportation purposes is assured predominantly by oil products (as shown in Section 2.2.1), with natural gas playing a negligible role; for instance, the quantity of oil and natural gas consumed in 2015 for transportation was 6245 ktoe vs. 13 ktoe, respectively.

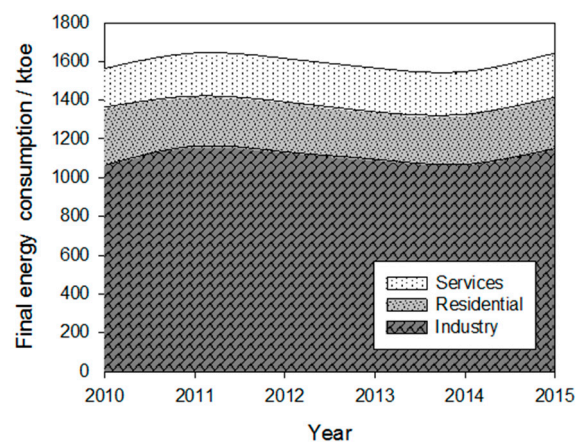


Figure 7. Natural gas for final energy consumption in Portugal by activity sector from 2010 to 2015 (data taken from [27]).

Table 3 lists the natural gas consumption across the industry sectors during 2005, 2014, and 2015.

Table 3. Natural gas consumption (ktoe) by the Portuguese industry (data taken from [27]).

Industry	2005	2014	2015	Δ (2015/2005)
Paper, Pulp, and Print	38.1	90.2	111.6	2.93
Construction	5.8	13.1	14.5	2.48
Chemical and Petrochemical industry	64.4	142.1	152.7	2.37
Food and Tobacco	66.5	124.6	147.2	2.21
Non-ferrous metal industry	7.6	12.9	16.0	2.09
Machinery	21.3	32.6	36.0	1.69
Iron & steel industry	41.4	47.4	51.1	1.23
Textile and Leather	128.6	131.4	131.9	1.03
Non-metallic Minerals (e.g., cement)	516.6	426.3	441.6	0.85
Wood and Wood Products	9.7	9.0	7.8	0.81
Mining and Quarrying	6.3	5.1	4.6	0.74
Transport Equipment	28.8	14.9	16.6	0.58
Non-specified (Industry)	20.9	7.2	5.8	0.28
Total	956.0	1056.8	1137.4	1.19

The values listed in Table 3 show that the non-metallic minerals sector is the biggest consumer of natural gas. Table 3 also highlights the growing relevance of natural gas over time. Indeed, since 2005, the annual consumption increased in eight out of 13 industrial activities (see relative variation in the last column). Amongst them, the paper, pulp, and print, the chemical and petrochemical, and the food and tobacco (2.21) industries stand out given their absolute energy consumption and relative variation

values, more than duplicating in all of them in only 10 years. Globally, natural gas consumption increased 19% in the 2005–2015 decade, which reflects its growing importance for the Portuguese industry sector.

2.3. Energy from Renewable Sources

The strategic effort to replace fossil fuels by energy from renewable sources has made Portugal one of Europe's leaders in this area [24]. Table 4 lists the amount (in ktoe) of energy from renewable sources produced in Portugal during the 2005–2015 decade.

Table 4. Portuguese annual production of energy from renewable sources (ktoe) from 2005 to 2015 [3].

Renewable Energy Type	2005	2007	2009	2011	2013	2015	Δ (2015/2005)
Biofuels	0	162	226	330	274	321	-
Electricity ¹	599	1265	1456	1872	2369	1927	3.2
Biomass ²	2773	2891	3019	2571	2812	2781	1.0
Other renewables ³	20	23	36	61	74	82	4.1
Total	3392	4342	4737	4835	5530	5110	1.5

¹ Includes the contribution of hydro, wind, photovoltaic, and geothermal power; ² includes the contribution of biogas; ³ includes solar (for thermal purposes) and (low enthalpy) geothermal sources.

Since 2006, Portugal has produced biodiesel, which is incorporated almost completely in the conventional fossil diesel and only a small fraction (ca. 1%) is directly sold in the market. Soybean and, particularly, colza oils are the most used raw materials [29]. More than half of the energy from renewable sources produced in Portugal comes from biomass, although that share decreased from 82% to 54%, when comparing the values of 2005 and 2015. The amount of energy produced from biomass remained nearly constant along the 2005–2015 decade, while the production of electricity tripled, reaching a share of 38% of the total energy from renewable sources produced in 2015 (cf. Table 4). Electricity production values shown in Table 4 include contributions from hydro, wind, photovoltaic, and geothermal sources, and excludes contributions from biomass in thermoelectric and co-generation plants. Information regarding the present energy production status from biofuels and biomass can be found elsewhere (e.g., [24]).

The investment made on the different technologies for power production from renewable sources is highlighted through the analysis of the installed capacity (MW) values listed in Table 5. The most established renewable energy sources (RES) for electricity production in Portugal are hydro and wind, both totaling over 90% of the installed capacity. Biomass is the third RES with a higher installed capacity, followed closely (in recent years) by photovoltaic, which remarkably increased from 3 MW to 451 MW in the 2005–2015 decade. During this period, the wind energy installed capacity increased almost 400% and was by far the type of RES with the highest absolute variation (i.e., 3971 MW).

Table 5. Renewable energy sources' installed capacity (MW) in Portugal for electricity production and corresponding variation in the 2005–2015 decade [3,30].

RES	2005	2007	2009	2011	2013	2015	Δ (2015/2005)
Geothermal	18	29	29	29	29	29	1.6
Photovoltaic	3	15	110	175	299	451	150.3
Biomass	429	449	518	712	718	726	1.7
Wind	1063	1699	3564	4378	4731	5034	4.7
Hydro	4816	4853	4883	5330	5533	6053	1.3
Total	6329	7045	9104	10,624	11,310	12,293	1.9

Among biomass, it should be mentioned the evolution of biogas production, whose installed capacity increased from 8 MW (in 2005) to 85 MW (in 2015), while the capacity for energy generation from urban solid wastes only increased 3 MW, reaching a total capacity of 89 MW in 2015.

The exploitation of the installed capacity for power production from the different RES is provided in Table 6, which shows that, globally, the power production tripled in the 2005–2015 decade. In the following sections, the status of each RES for producing electricity is addressed.

Table 6. Annual renewable power production (GWh) in Portugal and corresponding variation in the 2005–2015 decade [3,30].

RES	2005	2007	2009	2011	2013	2015	Δ (2015/2005)
Geothermal	71	201	184	210	197	204	2.9
Photovoltaic	3	24	160	282	479	799	266.3
Biomass	1651	1883	2086	2924	3052	3104	1.9
Wind	1773	4036	7577	9162	12,015	11,608	6.5
Hydro	5118	10,449	9009	12,114	14,868	9800	1.9
Total	8616	16,593	19,016	24,692	30,610	25,514	3.0

2.3.1. Geothermal

Among the RES, high temperature geothermal resources are confined to the Azores archipelago where this kind of energy plays an important role. Two geothermal power plants in operation at S. Miguel island, corresponding to a global installed capacity of 23 MW, are responsible for the production of 42% of the consumed electricity (i.e., around 22% of the archipelago total demand). Plans to increase the installed capacity up to 28.5 MW until 2019 have been reported [31]. The International Energy Agency (IEA) reported that enhanced geothermal systems technology, which uses thermal energy from high-temperature rocks (dry rocks) located at great depths, may be suitable to explore the potential geothermal resources in the mainland and be tested in the future [24]. Still, Portugal is the fifth country among IEA-29 members with the highest share of geothermal energy used for power production [24].

2.3.2. Photovoltaic

Power production in photovoltaic plants was negligible in 2005 and reached 799 GWh in 2015, being the RES with the highest relative variation in the 2005–2015 decade (cf. Table 6). Portugal has the best yearly solar irradiance in Europe after Cyprus, particularly in the Alentejo region, in the southern part of the territory, where the country has a current installed capacity of 162 MW (out of a total of 467 MW) [3,32]. The photovoltaic plant located in Moura is the largest in the country comprising an installed capacity of 46 MW. It is expected that solar energy will play an important role in decentralised power production, and a mini-generation programme created in 2011 has a target to install approximately 250 MW of new capacity by 2020 [24]. Before 2011, the lack of specific regulations for mini-generation systems limited photovoltaic diffusion as the feed-in tariffs settled in 2007 by the Decree-Law No. 225/2007 have not been listed explicitly, being calculated monthly for each system based on avoided costs, which leads to administrative difficulties as well as low transparency [33].

2.3.3. Biomass

The most common biomass resources available in Portugal are wood residues, animal waste, and municipal solid waste [32]. It was estimated that the country's total biomass potential is 42.5 TWh/year, with municipal solid wastes as the main resource (17.0 TWh/year) [32]. It has been reported that the use of municipal solid wastes, animal manure, and wastewaters are still underexploited [32]. In 2015, 586 GWh of power was generated from biogas and urban solid wastes (ca. 294 GWh each), together representing 19% of the total power produced from biomass (i.e., 3.10 TWh). Power production from

biomass is more developed in the center region of the country, representing 62% of the total power produced from biomass in 2015.

2.3.4. Hydropower

Hydropower production takes place in 184 hydropower plants, considering both large (≥ 10 MW) and small plants (< 10 MW) [34]. Portugal mainland's most important river basins are: Lima, Cávado, Mondego, Tejo, Guadiana, and, particularly, Douro, which is responsible for more than half of the hydropower generated in the country [3]. Portugal has storage, run-of-the-river, and pumped hydro storage type hydropower plants. Storage plants accumulate large quantities of water that can be used on the driest months, while run-of-rivers may include a small storage capacity, and turbines operate depending on the river's flow. Pumped hydro storage plants are conventional plants that were modified to include a system for pumping water from a lower elevation reservoir to a higher elevation. Generally, low cost power for running the pumps is provided by off-peak electricity generated from renewable energy sources, allowing the storage of that energy in the form of gravitational potential energy [35]. Portugal has a pumped hydro storage installed capacity of 2.44 GW [36].

Table 7 lists the hydropower generation per type of plant and river basin in the year of 2015. To the authors' knowledge, the values of power production through pumped hydro storage plants per river basin are not publicly available, but a global production of 1.16 TWh in 2015 was reported by Redes Energéticas Nacionais (REN, Lisboa, Portugal) [36].

Table 7. Hydropower generation (GWh) by type of plant and river basin in 2015 [3].

River Basin	Storage	Run-of-River	Total	%
Lima	484	5	489	5.0
Cávado	1180	29	1209	12.3
Douro	366	5422	5788	59.1
Mondego	322	88	410	4.2
Tejo	415	320	735	7.5
Guadiana	812	0	812	8.3
Others	0	355	355	3.6
Total	3579	6219	9798	100

Hydropower production in 2015 was affected by the hydrological conditions, and the amount of generated power was considerably lower than typical values found, representing only 60% of the power produced in 2014. Still, Table 7 highlights the importance of the global hydropower production of storage and run-of-river plants located in Cávado and Douro river basins, respectively.

2.3.5. Wind

Portugal had 255 wind parks with 2604 turbines in operation in 2015, corresponding to a total installed capacity of 5034 MW [3]. Figure 8 shows how the installed capacity, wind power production, and annual equivalent hours at full capacity (HFC)—ratio between the generated output (MWh) and the installed capacity (MW)—were distributed countrywide in 2015.

Figure 8 highlights that wind power production is massively obtained in the Center and North regions, together representing 87% of the overall production [3]. Globally, wind power was generated in 2305 equivalent hours at full capacity, with the North, Azores, and Madeira the only regions with an HFC lower than the global.

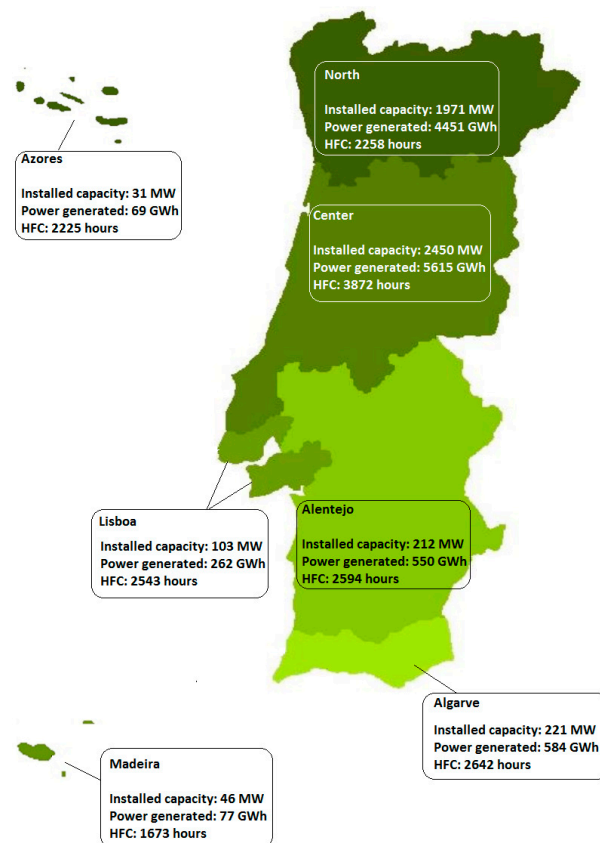


Figure 8. Wind power installed capacity, generation, and annual equivalent hours at full capacity (HFC) for the year 2015 (data taken from [3]).

The performance of wind turbines can also be expressed in terms of a capacity factor, where the number of equivalent hours at full load is normalized by the number of hours available in a given period, allowing assessment of the amount of power that was produced with respect to the maximum possible. Table 8 lists the capacity factor of each region for an ideal availability of 8760 h (i.e., hours available in one year without excluding shutdown periods (e.g., for maintenance)).

Table 8. Annual wind power capacity factor obtained in different regions of Portugal in 2015 (calculations based on data taken from [3]).

Region	Capacity Factor
Center	0.44
Algarve	0.30
Alentejo	0.30
Lisbon	0.29
North	0.26
Azores	0.25
Madeira	0.19

The annual capacity factor ranged from 0.19 (Madeira) up to 0.44 (Center), while the remaining regions had a value between 0.25 and 0.30. However, it is noteworthy to mention that the capacity factor can be considerably different depending on the period considered (year, month, etc.). Silva et al. [37] used historic wind power generation time series (up to five years) and reported that the capacity factor in Portugal can be 1.5 times higher in winter than in summer. The analysis on an hourly basis also showed that wind electricity generation is greater during base-load and off-peak periods. Unfortunately, the amount of wind power lost during these periods was not reported.

3. Perspectives for Power-to-Gas

3.1. Surplus Renewable Power

The IEA reported that instantaneous and daily renewable electricity output in Portugal regularly exceeds national demand and that the surpluses are either used in pumped hydro storage plants or exported [24]. Table 9 lists the amount of power that was consumed and produced in the country through pumped hydro storage in the period between 2010 and 2015.

Table 9. Pumped hydro storage power consumption and production (GWh) (calculations based on data taken from [27]).

Pumped Hydro Storage Power (GWh)	2010	2011	2012	2013	2014	2015	Δ (2015/2010)
Consumed	512	737	1331	1459	1081	1460	2.85
Produced	399	575	1038	1138	843	1139	2.85

Table 9 shows that the amount of surplus power consumed in pumped hydro storage plants almost triplicated in 2015 compared to the 2010 value; the storage round-trip efficiency is 78%. However, it should be recalled that pumped hydro storage plants represent huge capital investments and have been associated with several environmental impacts that are critical decisive factors [35,38]. Another option is to export the surpluses, in this case, to Spain. However, it has been reported that electricity from feed-in tariff supported technologies (like wind) is exported, and Portugal provides cheap electricity to Spain partially supported by the Portuguese Electricity System [39]. The feed-in tariff, a mechanism used by countries to foster the use of energy from renewable sources, is always paid to power producers independently of the power generated being used in Portugal or outside. Moreover, the tariff was guaranteed to power producers for a 20-year period, the longest reported among several European countries [39]. Therefore, it was recommended that exports should be reduced at high-generation moments, releasing the condition of feeding all renewables to the grid, and allowing for the spill of wind generation and/or investment in storage technologies [39].

Pumped hydro storage plants have been, to date, the main approach adopted in Portugal for the storage of excess renewable power. Decentralized units would, however, contribute to increase the country's storage capacity and foster energy transition as the substantial investment costs, appropriate geography, and inherent environmental impacts limit the extension of pumped hydro storage. To this end, power-to-gas technologies, particularly power-to-methane, could be selected based on the increasing consumption of natural gas (as discussed in Section 2.2.3), offering the possibility to integrate the power and gas grids. The renewable power is thus chemically stored as methane, which can be used on-site, injected into the natural gas grid, or stored in dedicated reservoirs, such as in salt caverns or in LNG tanks after being compressed.

Power-to-methane (PtM) applications in Portugal would benefit from the high quantity of installed wind power capacity within close distances of the gas infrastructure, with almost 60% of that capacity located less than 5 km to existing or future potential natural gas storage facilities, making Portugal a predestined country to implement PtM technologies, as long as adequate and nearby CO₂ sources are also available [6].

3.2. CO₂ Sources and Availability

The data presented in this section refers exclusively to greenhouse gas (GHG) emissions of CO₂ and not to other GHG species and their corresponding CO₂ equivalents. Figure 9 illustrates the evolution of CO₂ emissions in the country from 2005 to 2015, using data taken from the GHG emissions inventory regularly performed by the Portuguese Environmental Agency. It shows that CO₂ emissions are essentially divided into two categories: the most relevant class is related to CO₂ generated from the combustion of fuels for energy production (ca. 90% of all CO₂ emitted in 2015) and the other to

CO₂ produced in industrial processes. It should be recalled that emissions from biomass combustion are excluded from the national emissions totals since released carbon had been, in fact, fixed from the atmosphere by the photosynthetic process and, when it is burnt, returns to the atmosphere and does not increase the atmospheric/biosphere CO₂ pool [40]. However, CO₂ emitted from biomass combustion accounted for 11.5 Mt in 2015 [40].

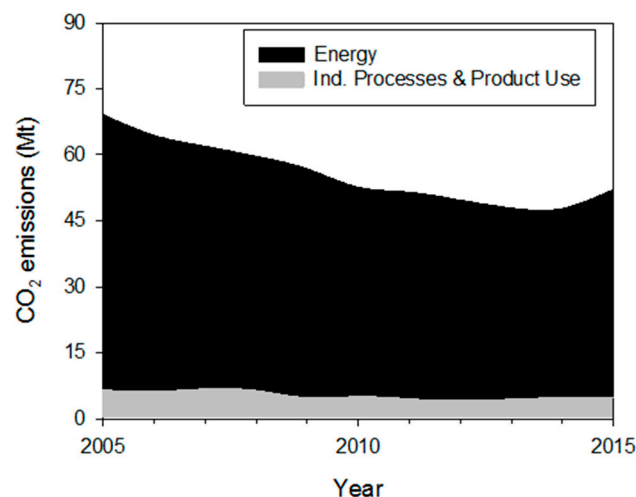


Figure 9. CO₂ emissions' evolution resulting from energy production and industrial processes and product use in Portugal for the period of 2005–2015 (adapted from [40]).

Regarding the evolution of the emissions history, Figure 9 shows that while CO₂ production from industrial processes remained almost constant in the reported period, the emissions due to energy production declined from 62.5 Mt to 42.9 Mt between 2005 and 2014 due to a combination of increased renewable power production and economic slowdown [24]. A slight increase of emissions was observed in 2015 (total of 52 Mt), which was a reflex of higher primary energy consumption for power production, namely of coal and natural gas. Additionally, final energy consumption also increased, particularly in road transport, natural gas, and electricity [40]. Figure 10 shows CO₂ emissions related to energy production in 2015 by type of sector and sub-sector.

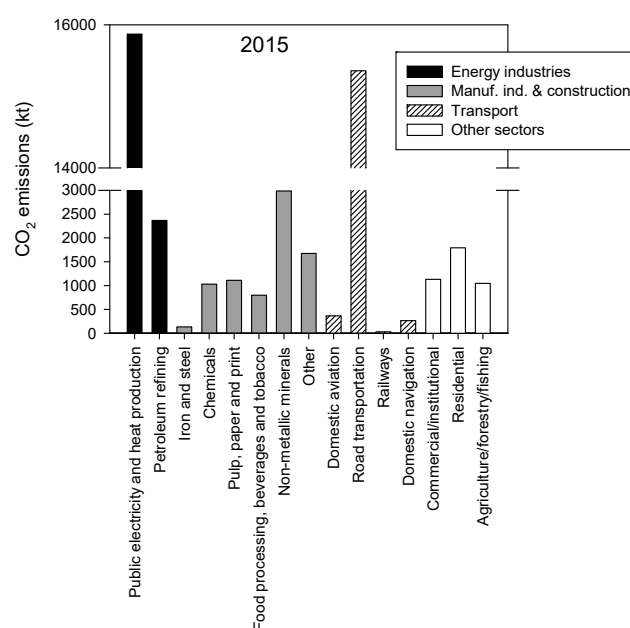


Figure 10. CO₂ emissions due to energy production by sector (2015) (adapted from [40]).

The amount of CO₂ emissions from public electricity and heat production and road transportation stand out amongst other sub-sectors (Figure 10). Together, these sub-sectors are responsible for 31 Mt of emitted CO₂, which corresponds to 60% of the national total. Afterwards, the non-metallic minerals sub-sector was responsible for the emission of 2981 kt of CO₂, being the principal emitter amongst the manufacturing industries and construction sector. The largest point emission sources for energy production considered were: 16 power plants, 2 oil refineries plants, 1 iron and steel industry, 1 petrochemical unit, 1 carbon black industrial plant, 8 paper pulp plants, and 6 cement plants. Besides energy production, the mineral industry also stands out in what concerns CO₂ emissions resulting from industrial processes (cf. Figure 11).

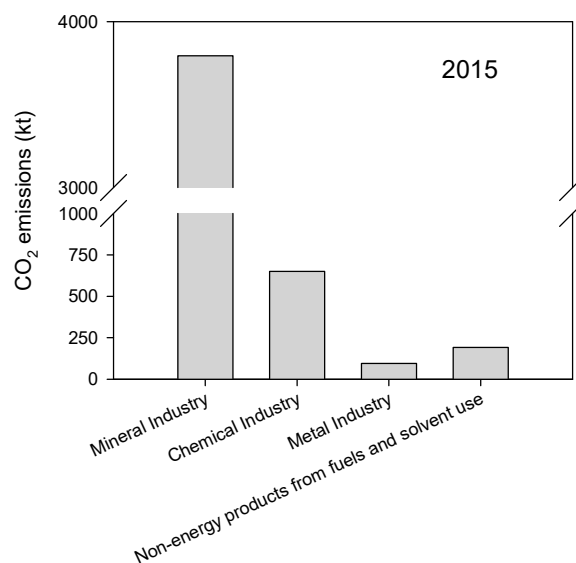


Figure 11. CO₂ emissions from industrial processes and product use (non-energy use) in 2015 (adapted from [40]).

The mineral industry sector was responsible for most of the CO₂ emissions in 2015 (3794 kt), with cement production being the most relevant activity with 2921 kt, followed by other processes, such as fertilizers (354 kt), lime (351 kt), and glass (167 kt) production (Figure 11). The second largest CO₂ emitter sector was the chemical Industry, namely by the petrochemical and carbon black production activity with 650 kt. The non-energy products from fuels and solvent use comprises emissions resulting from solvents, lubricants, and paraffin wax uses by several industries (e.g., plastics, wood products, rubber industry, and metalworking industry). CO₂ emissions associated to the metal industry come from secondary steel making.

From the analysis of Figures 10 and 11, it can be concluded that Portugal offers a wide variety of CO₂ sources, essentially diluted in flue gas streams, with a content between 5 vol. % (natural gas combustion) to 40 vol. % (e.g., cement) that can be selected to couple in power-to-methane applications, requiring, however, a previous CO₂ capture/purification stage to separate it from other contaminants. Criteria to select the best CO₂ source for power-to-methane applications include:

1. continuous access to CO₂ in a stream having low concentrations of severe poisons (e.g., H₂S and NO_x);
2. proximity to the national natural gas grid for methane injection to avoid/minimize storage and transportation costs;
3. proximity to renewable electricity plants that will power the water electrolysis unit in periods where production exceeds demand, minimizing distribution losses;
4. interest on recycling the methane produced, for instance, if the selected site has a natural gas co-generation plant (i.e., displacement of fossil fuels consumption); and

- interest on recycling the oxygen produced during water electrolysis to the process, which would further benefit the whole process from, at least, the economic point-of-view.

The CO₂ sources emitting more than 0.1 Mt/year in Portugal (data from 2007) and their geographic situation were identified by Carneiro et al. [41] and are illustrated in Figure 12.

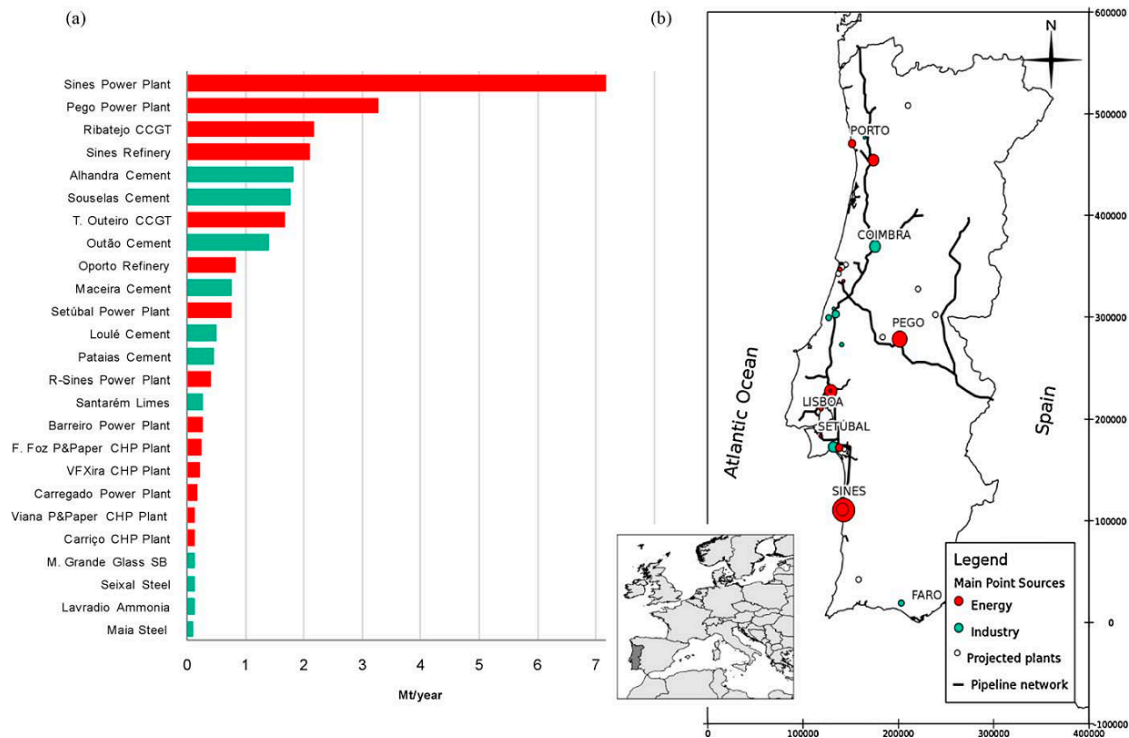


Figure 12. (a) CO₂ sources emitting more than 0.1 Mt/year in 2007 and (b) location of point sources and the natural gas network. Reprinted from International Journal of Greenhouse Gas Control, 5, J.F. Carneiro, D. Boavida, R. Silva, First assessment of sources and sinks for carbon capture and geological storage in Portugal, 538–548, Copyright (2011), with permission from Elsevier.

Figure 12 shows that all the main point sources are located close to the natural gas network, which, in addition to proximity to wind parks, as mentioned in the previous section, surely provides promising opportunities for PtG demonstration activities in the country, since CO₂ transport/storage practical difficulties and related cost uncertainties [11] might be avoided/minimized.

3.3. Natural Gas Grid

Portugal has a well-established natural gas storage, transportation, and distribution infrastructure (cf. Figure 13). The main pipeline goes next to the coast, from Sines until Valença do Minho (and onwards to Spain), where the main natural gas consumption points are located. It has several branches and two lines towards the interior of the country, one of which ends in Campo Maior and makes the connection with the Spanish pipeline in Badajoz (cf. Figure 13). This interconnection allows the country to receive up to 3.5×10^9 m³/year of natural gas from Spain, whose origins are in Algeria, while the interconnection in the north (Valença do Minho/Tuy) has a lower capacity (0.8×10^9 m³/year). Still, the highest entry capacity to the grid is provided by the LNG terminal in Sines (i.e., 5.3×10^9 m³/year) [24]. Both interconnections with Spain are fully reversible and a third one in Bragança/Zamora (dashed line in Figure 13) is planned and identified by the European Commission as a project of common interest [24,28].

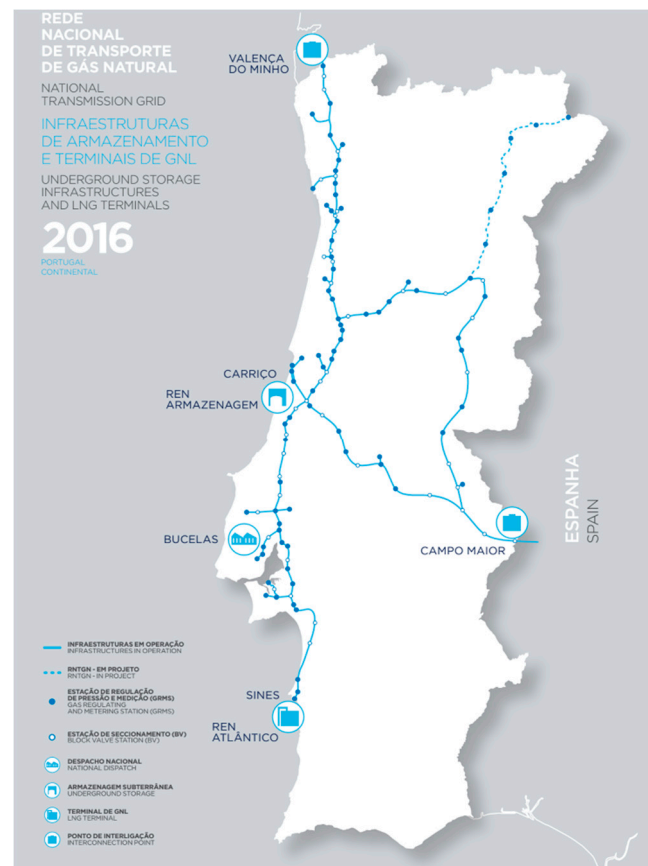


Figure 13. Portugal natural gas storage and transportation infrastructure (reprinted from [36] with permission from REN).

The national pipeline network has an extension of 1375 km with 202 pipeline stations [24]. Sines terminal receives LNG from large vessel ships with a capacity from 45×10^3 up to 216×10^3 m³. These ships unload into three LNG storage tanks having a combined capacity of 390×10^3 m³, corresponding to ca. 242×10^6 m³ of natural gas [24,36]. The terminal is equipped with five vaporizers using sea water as thermal fluid to gasify LNG, which is further compressed to 78 bar and injected into the gas grid [24]. The terminal facilities also include a filling station that may load up to 4500 tanker trucks a year to distribute natural gas to locations not covered by the pipeline network [24].

Another fundamental element of the national natural gas grid is the combined underground storage capacity of 333×10^6 m³ provided by six salt caverns located in Carrico. These caverns belong to the Monte Real salt structure of the Lusitanian basin, strategically placed in the middle of the main high-pressure pipeline (cf. Figure 13) [36,42]. The reasons for its construction were: (1) the storage of strategic reserves and (2) to balance supply and demand, namely due to seasonal and daily fluctuations, thus securing natural gas supply [42].

Carrico's underground storage facilities allow a gas injection and withdrawal of 110×10^3 Nm³/h and 300×10^3 Nm³/h, respectively. Before injection into the grid, the gas is filtered to remove solid and liquid particles, compressed, and dehydrated in a vertical absorber (the maximum final gas moisture content is 40 ppmv) [42].

The LNG terminal and Carrico salt caverns provide a total storage capacity of 575×10^6 m³. Considering that consumption in 2016 was 4.6×10^9 m³ [36], the existing combined capacity can stock the equivalent of the amount consumed by the country in 46 days. In the development plan of REN, the operator of the gas network, the construction of 25 new caverns in Carrico is forecasted to increase the storage capacity up to 1.25×10^9 m³ [43], although these expansion plans were reported to be currently under review [24].

Additional underground storage capacity in the Portuguese territory was estimated by Nunes [43]. Several criteria were adopted to choose the best locations. The criteria included rejecting zones that were in a close distance to airports, roads, and houses, inside protected areas, far away from the sea and gas grid, or not in a plain field. Afterwards, three regions were elected: Nazaré, Caldas da Rainha, and Peniche. The study considered a similar cavern volume and distance among the caverns, like the Carriço facilities, and an underground storage potential of $1 \times 10^9 \text{ m}^3$ was estimated. If the minimum distance to roads was limited to highways and railways, the storage potential reached $1.65 \times 10^9 \text{ m}^3$ [43]. Hence, a potential storage capacity of $3.14 \times 10^9 \text{ m}^3$ is envisaged, safeguarding 249 days of consumption (based on 2016 data). However, the preliminary assessment of the underground storage potential made by Nunes [43] should be complemented with the necessary environmental impact and economic studies. Recently, Carneiro et al. [20] screened priority sites for energy storage in geological formations using a geographic information system (GIS) and considered spatial, environmental, and social constraints, as well as the proximity to areas with wind or solar energy potential, accessibility to power transmission lines, and natural gas networks. The authors identified sites that could act as reservoirs for underground gas storage (of hydrogen or methane) (UGS), compressed air energy storage (CAES), underground pumped hydro energy storage (UPHES), and underground thermal energy storage (UTES); they concluded that, for the Portuguese geological context, the technologies with best application potential seem to be CAES and UGS linked to PtG.

Despite the envisaged underground storage potential yet to be explored, perspectives for PtG deployment in Portugal would be even more promising with the construction of the third planned connection with Spain in the natural gas network and of projected connections linking the Iberian Peninsula to France.

3.4. Research Needs

The current challenges regarding the technologies involved in PtG processes were extensively addressed in recent publications (e.g., [2,9,11,44]), and for that reason were out of the scope of this work, although their study has been the main focus of previous authors (e.g., [45,46]) and future research activities [19]. Instead, the present work aimed to provide a picture of the recent evolution of the Portuguese energy sector, highlighting the tremendous endeavor and commitment of the country for large-scale renewable energy deployment and to raise awareness about what seems to be promising conditions for PtG deployment. Nevertheless, future research studies to forecast surplus power in different energy case scenarios and the identification and characterization of the most suitable CO₂ point sources, besides techno-economic-environmental assessments, will be crucial to find profitable business models and integrated value chains for PtG deployment in Portugal. Among them, process chains should be looked at, leading to opportunities for O₂ (by-product of H₂O electrolysis) valorization, recycling of H₂O from CO₂ methanation, and energy integration to tackle current barriers for commercialization of PtG systems.

4. Conclusions

The present analysis of the Portuguese energy sector highlights the country's intense dependence on fossil fuels to afford its energetic needs, although, despite this, it was the fourth EU-18 member with the highest incorporation of renewables in power production in 2015 (i.e., 44.6%), a value that reached 57% in 2016 [36]. So far, the country's options to manage the energy surpluses generated by electricity from renewable sources relies on pumped hydro storage plants or power exportation to Spain. Hence, decentralized power-to-methane applications can be of strategic relevance for the country, since power production from natural gas will increase following the decommissioning of the Sines and Pego coal power plants by 2021. Storing surplus renewable electricity as methane would also allow the diversification of natural gas provision, minimizing the dependence and risk of shortage supply from foreign countries, as it is advised by the Portuguese Directorate-General for Energy and

Geology [47]. Additionally, a significant increase of natural gas consumption in the 2005–2015 decade (ca. 19%) by several and important industry sectors was also shown.

Portugal has important geographic advantages in favor of PtM demonstration projects, such as a well-developed natural gas network near wind parks and CO₂ sources, as well as a promising underground storage potential yet to be explored. For such a purpose, the engagement of all stakeholders (namely, academics, governmental bodies, technology and energy providers, major CO₂ polluting companies, and natural gas consumers) will be crucial for establishing national and/or regional research and development roadmaps, where the barriers (e.g., technical, legal, and regulatory), challenges, and opportunities for fast PtG deployment should be identified for coordinated actions.

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