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Market Opportunities in Portugal for the Water-and-Waste Sector Using Sludge Gasification

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Abstract: The water-and-waste sector has shown a marked interest in innovative management practices for dewatered sludge. The need to manage increased sludge volumes at rising disposal costs, coupled with the recognition of the potential for on-site energy production, have been the key drivers for this recent appeal. With the current political view supporting the development of a renewable-gas industry in Portugal, renewable gases are considered an attractive solution for dewatered-sludge valorization. Moreover, investment in renewable-gas supply chains would help the industry to mature to a level at which the technology and market are rapidly established. Recognizing this interest, dewatered-sludge gasification was selected as a possible valorization pathway, with the potential for hydrogen and bio-SNG production, as well as decentralized heat and power. This document identifies the market opportunities for the establishment of sewage-sludge gasification in Portugal. The analysis starts with a brief overview of the Portuguese water-and-waste sector, and a description of the current status of the renewable-gas markets. Finally, the dewatered-sludge amounts are quantified, and the potential for energy and renewable-gas production is estimated to support the interest in wastewater management in advanced processes, and to pave the way for future feasibility studies.

Keywords: sewage sludge; gasification; combined heat and power; hydrogen; biosynthetic natural gas; market analysis

Citation: Alves, O.; Garcia, B.; Rijo, B.; Lourinho, G.; Nobre, C. Market Opportunities in Portugal for the Water-and-Waste Sector Using Sludge Gasification. *Energies* **2022**, *15*, 6600. https://doi.org/10.3390/en15186600

Academic Editor: Gabriele Di Giacomo

Received: 3 August 2022
Accepted: 6 September 2022
Published: 9 September 2022

1. Introduction

Wastewater management in municipal communities plays an important role in minimizing environmental contamination, reducing odor emissions, and improving the population's health. Wastewater production is inherently associated with the social progress and development of urban areas. Generally, the Portuguese water-and-waste sector is structured into two main services: downstream (composed of wastewater collection, drainage, and elevation activities) and upstream (composed of wastewater transportation, treatment, and rejection activities). In 2019, the total domestic wastewater collected by downstream services in Portugal achieved 640×10^6 m^3 (equivalent to a production of 62 m^3 of wastewater per inhabitant), and 529×10^6 m^3 was collected by upstream services. This amount has remained almost constant since 2015, with some irrelevant fluctuations [1].

Municipal wastewater-sanitation services are structured into three fundamental stages: drainage (wastewater collection at origin), transport, and treatment [1]. Treatment is typically performed in dedicated wastewater-treatment plants (WWTPs), with the aim of adjusting the water parameters through the use of primary (physical), secondary (biological), and tertiary (advanced) techniques. These processes intend to retain the solid and oil residues, degrade the organic matter, and remove the phosphorous and nitrogen nutrients (especially when the final water is forwarded to sensitive areas) [2].

Beyond the final water stream with sufficient quality to be discharged into a natural water body, or to be reused in suitable applications (e.g., irrigation), WWTPs also produce a sewage-sludge stream that results from the different treatment stages in the plant. After additional post-treatments, such as dewatering and stabilization, this sludge maintains significant organic-matter content (60 wt.% db) and nutrients, as well as a significant heating value (12–20 MJ/kg db). Conversely, high levels of inorganic matter (11–76 wt.% db) and heavy metals may also be present [2]. Taking into account its characteristics, sewage sludge has been proposed as a raw material for bioplastic synthesis (polyhydroxyalkanoates) through bacterial fermentation, the production of adsorbents for the contaminant-removal processes, the extraction of enzymes, and the recovery of mineral fractions for construction materials (slags, bricks, and glasses) [3,4]. Due to their nutrient availability (in particular, their nitrogen, phosphorous, and organic contents), ability to provide moisture for soils, and capacity for pH regulation, sludges have been largely employed in agriculture for fertilization purposes [5]. In countries such as Norway, Estonia, and Ireland, the use of sewage sludge for agriculture practices reached more than 50% of the total amount that was disposed of by 2020 [6]. Despite this possibility of valorization, stringent regulations, and the possibility of environmental contamination (e.g., leaching of heavy metals), have limited this solution [5]. Incineration is another treatment that has been increasingly adopted by European countries, such as Germany and the Netherlands, as a way to reduce the sludge volume prior to landfilling. However, the use of incineration, as well as other recurring waste-elimination techniques (e.g., landfilling and ocean dumping), also pose environmental problems at a global level [3,7]. Nevertheless, a significant amount of sewage sludge is still being forwarded for fertilization and landfilling (16%). These drawbacks, along with the fuel properties exhibited by sewage sludges, have led to the exploitation of new alternatives for their energetic valorization.

Anaerobic digestion (AD) is a well-established process to convert sludge into biogas (or biomethane after further upgrading) through the decomposition of organic matter mediated by microbial communities in the absence of oxygen [8]. The process may also occur under a codigestion regime with other organic wastes (e.g., fruit waste), thereby promoting an increase in the methane yield. In countries such as Germany, Austria, and the Netherlands, WWTPs containing AD coupled with a combined heat and power (CHP) production unit have been deployed to generate energy for self-consumption [3]. Similar approaches have been implemented in the WWTPs located in Portugal, where, in general, the biogas is directly converted to electric energy [9]. Despite the lower technological maturity, other thermochemical processes, such as pyrolysis, supercritical water processing, and gasification, may be promising alternatives for the energetic valorization of sludges. Among these processes, gasification appears to be better positioned, which is essentially due to the celerity of material conversion, the versatility of added-value products, and the level of technological demonstration. In gasification processes, the feedstock is transformed into producer gas at high temperatures (800–1400 °C), which is rich in carbon monoxide and hydrogen, with the injection of low amounts of oxidant agents (e.g., air or oxygen) [2]. After its production, the producer gas is cleaned and conditioned, and it may be directly converted to heat and electricity (in gas engines or turbines), hydrogen (through water–gas shift and steam–methane-reforming reactions, combined with a final separation stage), or biosynthetic natural gas (bio-SNG) (through methanation) [10–12]. Currently, these strategies have already achieved commercial status using specific feedstocks, and in particular for the case of bio-SNG production. However, the option of hydrogen production still presents a lower degree of maturity, and it is only validated at the demonstration scale, with a technology-readiness level (TRL) of 5 [13,14]. Compared with AD, solutions based on sewage-sludge gasification present some drawbacks, such as the requirement of using dry feedstocks (typically with less than 20 wt.% of moisture), and higher bio-SNG production costs (EUR 20/GJ vs. EUR 15/GJ) [15,16].

Currently, there are two known sewage-sludge-gasification plants in operation, and one is being commissioned in Germany; they are all devoted to the generation of heat and power. These units have processing capacities of 2000–5000 t/y of dried sludge, and heat and power productions between 0.5 and 1.5 MW_{th} and 65 and 425 kW_e, respectively. Hence, the operation of these units demonstrates the practical implementation of sewage-sludge gasification at large scales, and the feasibility of valorizing such wastes into energy [17].

The recent European and Portuguese legislation (e.g., Directives 2018/2001/EU, 2019/692 and Decree-Law 62/2020), which promotes infrastructure development for renewable-gas production (namely, hydrogen and biomethane/bio-SNG), opens an opportunity for the implementation of gasification units across the country. Recognizing the important role of these gases for environmental decarbonization until 2050, the National Plan for Energy and Climate (*Plano Nacional de Energia e Clima* (PNEC) 2021–2030, Minister Council Resolution 53/2020) established specific targets for the renewable-energy consumption in different economic sectors (electricity, heat, and transport), where the hydrogen and biomethane demands are expected to increase in the upcoming years. As previously stated, these renewable gases may be produced via sewage-sludge gasification in dedicated centralized or decentralized plants, and eventually located near WWTPs suitable for process coupling. These actions could benefit the creation of new jobs, and the improvement and dynamization of local markets and economies.

The present document aims to identify the market opportunities in Portugal for the establishment of sewage-sludge gasification as a potential technology for heat, power, and renewable-gas production, and in particular hydrogen and bio-SNG. The study starts with a brief overview of the Portuguese water-and-waste sector, followed by a description of the current status of the renewable-gas markets at a national level, and it finally presents the results for the potential production of energy and gases from sludge gasification and the corresponding possible markets.

2. The Portuguese Water-and-Waste Sector

In Portugal, the water-and-waste sector is divided into two subsectors with different technological perspectives: one related to water-provisioning services, and the other related to municipal waste management. From a market-structure perspective, the sector is a classic example of a natural monopoly, where one entity delivers services in each geographical market due to the benefits from the scale and scope economies when providing water-and-waste treatment. Given this market concentration, both subsectors are monitored by ERSAR (*Entidade Reguladora dos Serviços de Águas e Resíduos*), which is responsible for the regulation of the quality of the services delivered to prevent market failures [18]. Concerning wastewater sanitation, the sector operates in a typical network, including stages related to discharge, drainage, elevation, transport, treatment, and the rejection of the treated water. These services can be supplied by private or public entities, and they are normally divided into the infrastructure required for collecting, transporting, and elevating wastewater from households (downstream systems), and the infrastructure responsible for the connection for the transport, treatment, and rejection in the receiving medium (upstream systems) [19]. The Portuguese legal framework allows three management models: (i) direct management (via municipalities, municipalized services, and associations of municipalities); (ii) delegated management (via parishes, municipal-owned companies, or companies established in partnership with the state); and (iii) management contracted out to the private sector (via public–private partnerships) [19]. On the one hand, the downstream infrastructures are generally managed by municipalities, and especially in low-population areas. The subsector is very fragmented, and it includes 253 management entities, mostly of small sizes. On the other hand, most upstream systems are managed via concession contracts, with only 12 management entities responsible for the wastewater sanitation of more than 96% of the population and 90% of the municipalities [1,19]. The *Águas de Portugal* (AdP) group, for example, aggregates several of the most important companies and provides services to over 7.5 million people in 222 municipalities, with 980 WWTPs distributed around the country [20]. The main company recently launched an innovation strategy that is 360° focused on water reuse, showing that the organization is open to innovation in many areas [21].

In Portugal, the water-and-waste sector has been guided by a series of strategic plans. PENSAAR 2020 (*Nova Estratégia para o Setor de Abastecimento de Água e Saneamento de Águas Residuais*), which succeeded PEAASAR 2007–2013 (*Plano Estratégico de Abastecimento de Água e de Saneamento de Águas Residuais*), was the last reference instrument used to shape the development of the water provision and wastewater sanitation in Portugal, and it allowed a marked evolution in the coverage and quality of the public services delivered. As an example, more than 85% of buildings were supplied with downstream wastewater-sanitation systems in 2019, serving about 8.6 million inhabitants [19]. However, the sector is currently facing new challenges. An increasingly relevant aspect is related to sludge management. The most recent figures indicate that the dewatered sludge exceeded 120,000 and 420,000 t/y in the downstream and upstream systems, respectively, with no clear policy regarding adequate final uses beyond traditional agricultural valorization. PENSAARP 2030 (*Plano Estratégico para o Setor de Abastecimento de Água e Gestão de Águas Residuais e Pluviais 2021–2030*) is currently being discussed, and it may partially address these issues by providing a novel vision and specific energy-efficiency and sludge-management goals. Either way, technological processes to transform wastewater sludge into a valuable resource, centered on nonagricultural techniques within the scope of a circular economy, need to be adopted and developed. Taking advantage of the current political environment, the production of renewable gases via gasification is a promising solution to this sludge generation in the current WWTPs.

3. Potential Final Markets for Gasification-Based Sludge Valorization

Energy-neutral wastewater treatment is increasingly viewed as a critical achievement in the water-and-waste sector to reduce energy consumption and greenhouse-gas (GHG) emissions. In Portugal, wastewater sanitation was responsible for the consumption of around 430 GWh during 2019, with less than 10% resulting from its own production of energy [19]. Hence, many companies in the sector already have strategic goals of increasing the in-house energy production, and there is an interest in the implementation of novel energy-recovery-process configurations. On a wider level, renewable gases, such as hydrogen and biomethane/bio-SNG, are also the two essential pillars of many decarbonization strategies, including the Portuguese Roadmap for Carbon Neutrality 2050 (RNC 2050—*Roteiro para a Neutralidade Carbónica*) [22]. These advanced energy carriers are expected to play an important role in the EU's goal of cutting GHG emissions, and there is a strong need to accelerate the market deployment, with developments required on the whole value chain. The supply, for example, will have to increase significantly in the next few years in each member state, with the involvement of sectors with the potential to produce valuable waste, such as the water-and-waste sector in Portugal.

3.1. Combined Heat and Power (CHP)

In situ energy production in CHP systems is a feasible energy-positive process configuration used in many WWTPs. Generally, increasing the energy self-sufficiency in domestic wastewater treatment is achieved through the production of biogas via AD, with subsequent energy production in gas engines or turbines. An alternative is the use of gasification CHP to convert dewatered sludge into producer gas. Gasification is also adequate for decentralized small-scale applications, with the cleaned syngas meeting the quality requirements of heat and power generating units. Therefore, the gasification market for energy production in CHP systems should expand in the coming years, and it should be of interest to the water-and-waste sector as a strategy for improving sludge management and recovering energy via a complementary process (also in the framework of PENSAARP 2030).

3.2. Hydrogen

Hydrogen, as a possible zero-carbon energy carrier, has been presented as the main contender for low-carbon transportation fuel and industrial decarbonization in sectors in which full electrification is not a viable option [23]. Hydrogen can be produced from different energy pathways and feedstocks, including the gasification of sludge from the water-and-waste sector [24]. Hydrogen is currently imported into Portugal, or it is produced in the Sines Refinery from nonrenewable sources. There is virtually no domestic green hydrogen production in Portugal, but the situation is expected to change in the next decade. The hydrogen national strategy (EN-H2—*Estratégia Nacional para o Hidrogénio*) has been created to accelerate the introduction of hydrogen into the domestic energy market [23]. As an example, EN-H2 foresees a gradual introduction of hydrogen into the road and maritime sector (shares between 20 and 25% in 2050), and an increase in refueling stations (from 10 to 25 in 2025 to from 1000 to 1500 in 2050). The number of heavy-freight vehicles is expected to increase accordingly [23]. As a substantial user of heavy-duty vehicle fleets in day-to-day activities, the water-and-waste sector may be considered a first mover in promoting a novel hydrogen market in Portugal. These markets can now be supported by guarantees of origin in the framework of Decree Law 60/2020. Together with feasibility studies, this certification would validate the sustainability of gasification to potential suppliers, such as management entities in the water-and-waste sector, helping the domestic establishment of the technological pathway. Ideally, certificate-of-origin platforms, such as "blockchain fractional contracts", would open opportunities for smaller green hydrogen producers, including small management entities running specific WWTPs. These platforms would also enable the aggregation of bundles of independent decentralized producers, allowing them to overcome high market barriers because of initial capital costs and other restrictions to market entry [24].

3.3. Biomethane/Bio-SNG

Biomethane/bio-SNG is a potential carbon-negative fuel that is capable of being used in several energy applications, including the gas sector and some mobility segments. In Portugal, biomethane is still produced in low quantities, mainly using waste feedstocks, such as WWTP sewage via biogas upgrading after AD. Nevertheless, alternative bio-SNG production via gasification is expected to gain relevance in the water-and-waste sector, and especially for the valorization of dewatered sludge. A small biomethane supply chain has emerged in Portugal in recent years. Biomethane is supplied in the compressed and liquified state for use in gas vehicles in several refueling stations operated by *Douro Gás Renovável* [25,26]. Much like hydrogen, this market segment is of particular interest for the water-and-waste sector, as many of its activities rely on the operation of heavy-duty vehicles. Fleet operators have the potential to run vehicles on predefined routes with 100% biomethane/bio-SNG, and thus this sector can be viewed as an early adopter of renewable gas, and it has helped to establish a domestic biomethane/bio-SNG gas market. Other promising final markets are the distribution of biomethane/bio-SNG through the Portuguese gas grid, or the total or partial conversion on site to increase the energy self-sufficiency in wastewater treatment.

4. Sewage-Sludge Production in Portugal and Potential Valorization Pathways

The potential of the water-and-waste sector, and in particular wastewater sanitation, to produce gasification-based gas products can be estimated via the total amount of dewatered sludge generated in WWTPs. In this report, the main pathways chosen for sludge valorization were CHP and the production of renewable gases, namely, hydrogen and bio-SNG, to help improve the energy self-sufficiency in domestic wastewater treatment and Portugal's decarbonization targets. The main goal is to perform a prospective technological study to improve the sludge management in Portugal. As such, environmental and techno-economic uncertainty is not fully examined and should be addressed in future studies at the request of interested companies from the sector. In fact, thermochemical technologies can include several process configurations that may influence energy integration and the final gas production, but scalability is often an issue in emerging pathways. For convenience, a specific technological pathway is assumed for each scenario to demonstrate the potential of gasification-based sludge valorization.

4.1. Base Scenarios and General Assumptions

Wastewater sanitation produces significant amounts of sewage sludge with the potential for energy recovery. This sludge is usually dewatered in WWTPs before final disposal by a licensed contractor, but virtually no energy is recovered from the current management practices. In 2019, the sector generated more than 120,000 and 420,000 t/y of dewatered sludge in the downstream and upstream systems, respectively, with management entities such as *Águas do Tejo Atlântico*, TRATAVE, *Águas do Centro Litoral*, *Águas do Algarve*, and others aggregating most of the production (Table 1) [1]. For simplicity, the analysis was limited to managing companies belonging to the AdP group (*Águas da Região de Aveiro* is excluded due to the low sludge amounts generated).

Table 1. Dewatered sludge generated by the top wastewater-sanitation-management entities (AdP group managing companies in bold) [1].

Management Entity	Type of System	Amount (t/y)
Águas do Tejo Atlântico	**Upstream**	**162,551**
TRATAVE	Upstream	53,765
Águas do Centro Litoral	**Upstream**	**50,409**
Águas do Algarve	**Upstream**	**45,902**
Águas do Norte (multimunicipal concession)	**Upstream**	**37,821**
Águas do Porto	Downstream	26,428
Águas do Vale do Tejo	**Upstream**	**21,639**
SIMDOURO	**Upstream**	**20,959**
Aquanena	Downstream	19,881
SMAS de Almada	Downstream	16,511
SIMARSUL	**Upstream**	**14,361**
Águas de Barcelos	Downstream	9886
AGERE	Downstream	9615
Águas de Valongo	Downstream	9135
Indaqua Matosinhos	Downstream	6754
Águas do Sado	Downstream	6452
Águas Públicas do Alentejo	**Upstream**	**6325**
SMAS de Viseu	Downstream	4606
SMAS de Sintra	Downstream	4450
SMAS de Caldas da Rainha	Downstream	4304
Águas de Santo André	**Upstream**	**4298**
EMAS de Beja	Downstream	4140
Águas da Figueira	Downstream	4114

Based on the previously described potential of sludge gasification, three base configuration scenarios for energy and renewable-gas production were selected: heat-and-power (Figure 1a), hydrogen (Figure 1b), and bio-SNG (Figure 1c) production.

The initial dewatered sludge received by the plant was assumed to have moisture and ash contents of 78.5 wt.% wb and 42.12 wt.% db, respectively. All plant scenarios contain common processes that include, in particular, a feedstock pretreatment stage (composed of thermal drying and pelletization), gasification stage, and gas-cleaning stage. Thermal drying ensures that the sludge presents an adequate moisture content (15–20 wt.% wb), while pelletization is applied to obtain dried sludge particles with regular dimensions and a good mechanical consistency for efficient thermochemical gas conversion. Gasification is conducted in a fluidized-bed reactor containing a turbulent catalytic bed, with the aim of enhancing the gas yield and quality in terms of the hydrogen content and heating value [15,27,28]. The main operating parameters used to estimate the gas production were the following:

- Reactor type: fluidized bed;
- Oxidant agent: air;
- Bed material: 60 wt.% sand + 40 wt.% alumina;

- Equivalence ratio: 0.3;
- Temperature: 850 °C;
- Syngas yield: 2.57 Nm^3/kg daf [28].

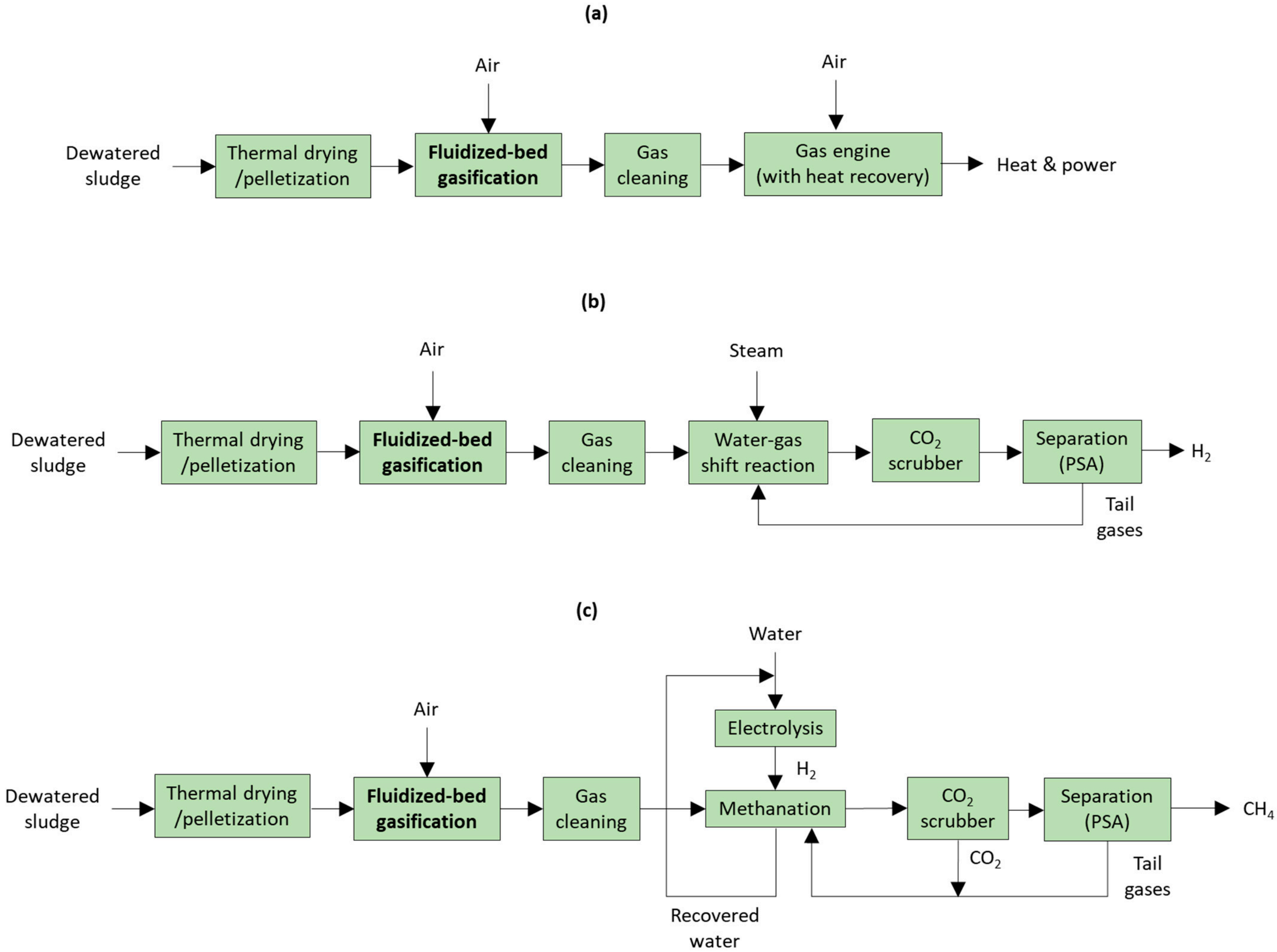

Figure 1. Configuration scenarios for energy and renewable-gas production from dewatered-sludge gasification: (**a**) CHP production; (**b**) hydrogen production; (**c**) bio-SNG production.

After gasification, the producer gas is decontaminated in the gas-cleaning module, which consists of a cyclone (to remove coarse particles), a rapeseed methyl ester (RME) scrubber (to retain tars), a bag filter (to separate fine particles), and a final water scrubber (to retain trace contaminant gases, namely, chlorine, sulfur, and ammonia) [29]. This cleaning procedure allows the final syngas to have adequate characteristics for energy conversion or renewable-gas production in the next stages, and particularly in terms of low concentrations of contaminants, which promotes better process efficiency and avoids operational issues in downstream equipment. A way to recover sensible heat from the ash deposited at the bottom of the gasifier would be to use a stream of air as a cooling medium for the ash itself [30]. This cold air, when used as a medium for heat recovery, would then be sent to the gasifier, therefore participating in the oxidation reactions involving the sludge, and keeping the total volume of the product gas constant at the exit. The use of this hot air would contribute to keeping a stable and high temperature during gasification, without the additional heat production obtained from an increased feedstock consumption. Moreover, it can also be assumed that this hot air combined with another heat source (e.g., solar radiation) can help reduce the energy costs of the sludge thermal-drying step, introduced previously in all scenarios of Figure 1 [31,32]. The plant was assumed to operate at 7500 h/year, and the syngas was considered to have the composition described in Table 2, with a final lower heating value (*LHV*) of 3.9 MJ/Nm^3 [28,33].

Table 2. Main producer-gas composition assumed for dewatered-sludge gasification [28].

Compound	Concentration (vol.%)
H_2	8.67
N_2	62.69
CO	8.81
CH_4	2.20
CO_2	15.61
C_2H_4	1.69
C_2H_6	0.04
C_2H_2	0.09
H_2S	0.20

Based on the previous assumptions, the estimated annual amounts of syngas obtained from dewatered-sludge gasification are presented in Table 3.

Table 3. Estimated syngas amounts obtained from dewatered-sludge gasification for each managing entity (AdP group).

Management Entity (AdP Group)	Mass of Sludge (t/y daf)	Syngas (t/y)	Syngas ($\times$1000 Nm^3/y)
Águas do Tejo Atlântico	20,228	64,858	51,986
Águas do Centro Litoral	6273	20,113	16,122
Águas do Algarve	5712	18,315	14,680
Águas do Norte	4707	15,091	12,096
Águas do Vale do Tejo	2693	8634	6920
SIMDOURO	2608	8363	6703
SIMARSUL	1787	5730	4593
Águas de Santo André	535	1715	1375
TOTAL	44,543	142,819	114,475

A total volume of c.a. 114,475 Nm^3/y of syngas was estimated for all entities, with *Águas do Tejo Atlântico* showing the greatest contribution (45%), followed by *Águas do Centro Litoral* (14%), *Águas do Algarve* (13%), and *Águas do Norte* (11%). These syngas volumes may be further converted to heat and power, hydrogen or bio-SNG, using specific production schemes implemented after the gasification stage. Three scenarios based on the possible process systems are described in the next sections to estimate the corresponding production potentials.

4.1.1. Base Scenario 1: Sludge to CHP

CHP is a highly efficient process that converts solid wastes and biomass into useful energy with higher efficiency when compared with electric energy production alone. In general, the heat recovery for new applications increases the global energy efficiency of the process to a range of 60–80%. Moreover, the carbon emissions may be lowered (−49%), and the overall process reliability is better [34,35].

Considering this strategy, heat and power can be simultaneously generated through two basic schemes: a combustion turbine/engine and steam boiler/turbine. Both schemes integrate an engine/turbine connected to a generator to produce electricity, with the possibility of recovering useful heat from the exhaust gases/steam at the exit for hot-water or steam production for subsequent applications. The main difference between both schemes relies on the heat source used to feed the main process (direct fuel injection and steam production from an auxiliary boiler, respectively) [35].

For the configuration of the heat and power production module, a gas engine with heat recovery was considered, with electric and thermal conversion efficiencies of 23% and 42%, respectively (Figure 1a). Therefore, the total energy efficiency of the CHP unit reached 55%. The heat produced can be partially or totally used for sludge drying at the pretreatment stage, thereby enhancing the global energy efficiency of the process. The remaining fraction can be applied for other purposes (for instance, district heating [36]). For energy calculations, a *LHV* of 3.9 MJ/m^3 was assumed for the syngas [28]. The annual electrical energy output (E_e, in MWh$_e$/y), annual heat output (E_{th}, in MWh$_{th}$/h), and power production for 7500 h/y of continuous plant operation (P_e, in MW$_e$/y) were estimated through Equations (1)–(3), respectively:

$$E_e = V_{gas} \times LHV_{gas} \times \eta_e / 3600 \quad (1)$$

$$E_{th} = V_{gas} \times LHV_{gas} \times \eta_{th} / 3600 \quad (2)$$

$$P_e = E_e / 7500 \quad (3)$$

In these equations, V_{gas} is the annual production of gas through gasification (Nm^3/y), LHV_{gas} is the lower heating value of the gas (MJ/Nm^3), and η_e and η_{th} are the production efficiencies of the electric energy and heat in the CHP unit, respectively. Table 4 presents the results for the potential heat and power production from dewatered-sludge gasification for the considered managing entities.

Table 4. Estimated heat and power production from dewatered-sludge gasification for different WWTPs from the AdP group.

Management Entity (AdP Group)	Potential Annual Electrical Output (MWh$_e$/y)	Potential Annual Thermal Output (MWh$_{th}$/y)	CHP-Estimated Electrical Output for 7500 h (MW$_e$/y)
Águas do Tejo Atlântico	12,953.28	23,653.81	1.73
Águas do Centro Litoral	4016.97	7335.33	0.54
Águas do Algarve	3657.81	6679.49	0.49
Águas do Norte	3013.86	5503.57	0.40
Águas do Vale do Tejo	1724.36	3148.83	0.23
SIMDOURO	1670.17	3049.88	0.22
SIMARSUL	1144.39	2089.76	0.15
Águas de Santo André	342.50	625.43	0.05
TOTAL	28,523.33	53,086.09	3.80

The total electrical and thermal energy production can achieve 28,523 MWh$_e$ and 53,086 MWh$_{th}$, respectively, with the greatest energy potential presented by *Águas do Tejo Atlântico* (45%). The electricity generated would be valuable for grid injection, while the heat might be applied for internal use or other local applications. However, several entities showed very small power outputs (<1 MW), which may not help the economic viability of the gasification plants located in their operating regions, considering a decentralized implementation strategy. In particular, the heat required for sludge drying is expected to be significantly high, which would decrease the overall economic feasibility for small-plant projects. A possible solution would rely on the reduction in the plant operating period (<7500 h/y) to increase the energy-flux output, but this may lead to longer periods of inactivity. The best approach for a CHP-based solution seems to be the use of centralized plants located in strategic points over the territory, with the aim of increasing the power output and maintaining a long period of plant operation.

4.1.2. Base Scenario 2: Sludge to Hydrogen

The hydrogen concentrations in the syngas produced from noncatalytic biomass gasification are generally low. Nonetheless, a simple pressure-swing-adsorption (PSA) unit can be used for hydrogen purification after syngas cleaning. In general, PSA tail gases are combusted in a CHP engine to produce electricity and heat for use in the process, while the pure hydrogen stream is compressed for distribution or grid injection. The hydrogen fraction, however, can be increased by a previous water–gas shift reaction (WGSR). This process is a redox-type reaction that is expressed by Equation (4):

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \ \Delta H_{298} = -41.1 \text{ kJ/mol} \tag{4}$$

WGSR pertains to a reversible and moderately exothermic group of reactions, and it will be triggered when carbon monoxide and steam coexist in the same environment and the energy barrier of the chemical reaction is overcome [37]. Catalytic WGSR has been generally tested at 450 °C, with a wide variation in the reported values of the catalyst stability (4–20 h), CO conversion (58–98%), hydrogen yield (32–89%), and selectivity (18–99%) [38]. Ni-based catalysts are widely used and have very high CO conversion, but they generate unwanted methane that reduces the hydrogen yield. This collateral methanation can be prevented by adding potassium with an optimum loading of 5 wt.% [37]. Several factors, such as the facility size and feedstock cost, affect the economics associated with hydrogen production through WGSR.

In the present study, the proposed baseline configuration for renewable-hydrogen production from dewatered-sludge gasification is illustrated in Figure 1b. After the removal of impurities, the syngas is conducted to a WGSR reactor (parameters of 91% CO conversion ratio and 47.6% hydrogen yield), thereby boosting the hydrogen fraction present in the gas mixture. Then, the gas passes through a CO_2 scrubber and is finally purified in a PSA filter, producing hydrogen that is >99.98% pure, and with a total recovery of 97.06% [39]. The hydrogen is then compressed and stored in a tube trailer for distribution or sale, while the tail gases generated by the PSA filter may be recovered and conducted back to the WGSR.

Considering all these assumptions, the annual-hydrogen-production potentials under this scenario for the different management entities are presented in Table 5.

Table 5. Potential-hydrogen-production values from dewatered-sludge gasification provided by management entities from AdP group.

Management Entity (AdP Group)	Annual-Hydrogen-Production Potential ($\times$1000 Nm^3/y)	Annual-Hydrogen-Production Potential (t/y)
Águas do Tejo Atlântico	6478	565
Águas do Centro Litoral	2009	175
Águas do Algarve	1829	159
Águas do Norte	1507	132
Águas do Vale do Tejo	862	75
SIMDOURO	835	83
SIMARSUL	572	50
Águas de Santo André	171	15
TOTAL	14,265	1245

A total hydrogen amount of c.a. 1245 t/y was estimated for the current scenario, with *Águas do Tejo Atlântico* presenting the greatest production potential (45%). This amount is equivalent to 49,063 MWh of useful energy, and it may be used in diverse applications, such as heat, electricity, grid injection, and transportation. Hydrogen production is one of the base pillars regarding the national plans for decarbonization, such as PNEC 2021–2030 and EN-H2.

4.1.3. Base Scenario 3: Sludge to Bio-SNG

After cleaning and removing the producer-gas contaminants, the CO and CO_2 can be combined with H_2 to produce bio-SNG (CH_4). The comethanation of these gases includes a series of exothermic reactions that are typically performed in a temperature range of 300–550 °C, and under pressures from 1 to 100 bar [11]. As presented below (Equations (5) and (6)), these main reactions must occur with appropriate H_2/CO ratios (from 3:1 to 5:1) to achieve the maximum efficiency and avoid carbon deposits in the catalysts [40]. Hence, when using syngas as the precursor of methanation, additional H_2 is needed for the process, and it can be obtained by water electrolysis using renewable energy:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O\ \Delta H_{298} = -165\ \text{kJ/mol} \quad (5)$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O\ \Delta H_{298} = -206\ \text{kJ/mol} \quad (6)$$

The baseline configuration scenario for renewable-bio-SNG production from dewatered-sludge gasification was established for this study according to Figure 1c. After a stage of cleanup and the removal of impurities, the syngas is fed into a fixed-bed methanation reactor, along with hydrogen produced by electrolysis, considering a H_2:CO ratio up to 5:1. A second methanation step ensures the complete CO removal from the methane-rich gas, and it also limits the outlet temperature to 650 °C to avoid catalyst sintering. After methanation, the gas is cooled and fed into a scrubber, with the aim of reducing the CO_2 concentration, before the removal of the moisture by condensers and desiccant filters. These steps help to achieve greater efficiency in bio-SNG purification by means of a multistage vacuum PSA, which is able to fulfill the grid quality requirements (99% of pure CH_4) and to recover 99.96% of the CH_4 [41]. Tail gases from the vacuum PSA and CO_2 scrubber are reintroduced back into the methanation reactor, while the water generated can be recovered to feed the electrolyzer. Regarding tail gases, an alternative is to vent them off to the atmosphere once they do not represent a problem for health or the environment. As before, the purified bio-SNG can be compressed and stored in tube trailers for distribution or grid injection. Table 6 shows the predicted results for the annual bio-SNG production obtained from dewatered-sludge gasification.

Table 6. Potential bio-SNG production values from dewatered-sludge gasification provided by management entities from AdP group.

Management Entity (AdP Group)	Annual Bio-SNG Production Potential (×1000 Nm^3/y)	Annual Bio-SNG Production Potential (t/y)
Águas do Tejo Atlântico	5142	3377
Águas do Centro Litoral	1595	1047
Águas do Algarve	1452	954
Águas do Norte	1196	786
Águas do Vale do Tejo	684	450
SIMDOURO	663	435
SIMARSUL	454	298
Águas de Santo André	136	89
TOTAL	11,323	7436

According to the previous assumptions for bio-SNG production, a total amount of 7436 t/y was estimated, with an energy content of 114,713 MWh. Again, *Águas do Tejo Atlântico* presented the greatest potential for bio-SNG production (45%). In terms of energy, the bio-SNG potential was superior in comparison with the previous scenarios of hydrogen production (49,063 MWh) and CHP (total of 81,609 MWh_{e+th}), and therefore bio-SNG presents huge opportunities and is suitable for grid injection or transportation. This opportunity is also in line with some government plans and targets that advocate the use of renewable gases in the national energy system, as already referred to for the case of hydrogen production.

4.1.4. Comparison of Technical, Economical, and Greenhouse-Gas-Emission Aspects between the Different Base Scenarios

In the technical domain, Scenarios 2 and 3, based on hydrogen and bio-SNG production from sewage sludge, respectively, are more demanding in what concerns the product-gas-purification requirements after gasification (gas-cleaning module), when compared with the situation of Scenario 1 (CHP production). The use of specific catalysts (WGSR and methanation modules), organic solvents (CO_2 scrubber), and adsorbents (PSA) implies that a deeper purification of the product gas was generated, with the aim of reducing the contaminant concentrations to very low levels (e.g., tars, sulfur, and nitrogen compounds, acid gases and metals) that would cause problems in the saturation and degradation of consumables, as well as a reduction in the yield of hydrogen or bio-SNG [42,43]. Moreover, Scenarios 2 and 3 would require additional consumables to execute several gas-cleaning and conversion steps, as well as the availability and preparation of other secondary feedstocks, and in particular, water and steam for the WGSR and electrolysis. Such observations would have implications in both CapEx and OpEx for the overall plant, which would therefore be higher compared with the CHP scenario. However, to minimize these economic repercussions, other technical solutions may be considered to increase the hydrogen concentration in the product gas, which would be beneficial for both hydrogen and bio-SNG production. These technical solutions may include, for instance, the admission of steam into the gasifier instead of air, and an increase in the moisture content in the inlet sewage sludge, the use of efficient catalysts in the gasifier bed, or the inclusion of additives in the feedstock, such as dolomite, olivine, and lime [44–46].

From an economic perspective, assuming the same production values previously calculated for the different products, and approximated selling prices of EUR 38.9/GJ, EUR 12.5/GJ, EUR 21.7/GJ, and EUR 44.2/GJ for electricity, heat, hydrogen, and bio-SNG, respectively, the total profits obtained from the three production scenarios would be estimated at EUR 638.2 k/y for CHP, EUR 323.7 k/y for hydrogen, and EUR 1642.1 k/y for bio-SNG [47–49]. These results demonstrate that bio-SNG production would be the most profitable scenario. However, the effective economic balance resulting from the different scenarios would be lower than the previous values after deducing all the operation costs and investments associated with the different processes. As reported in the previous section, the gasification of sewage sludge to generate bio-SNG appears to be the best scenario for implementation in Portugal, not only because it produces more fuel (in energy basis), but also because it presents the most attractive profit in the end. In addition, biomethane represents an energy carrier that is more flexible than the on-site production of heat and power, as it can be transported and stored in other locations to be used (e.g., terrestrial transports and national gas grid). This scenario is aligned with the recent European policies and government efforts to encourage the share of bio-SNG in the national energetic chain (e.g., PNEC 2021–2030 and the European RePowerEU action plan for 2030), thus benefiting from possible incentives in the near future.

At an environmental level, the greenhouse-gas (GHG) emissions are expected to be lower in Scenario 1 with CHP production, as the lower complexity of the process and the admission of fewer consumables and other secondary feedstocks (e.g., catalysts, adsorbents, and steam) would result in a lower carbon footprint caused by the manufacturing and preparation of additional resources. Such resources are mainly required during the product-gas conversion and tuning steps to obtain bio-SNG and hydrogen in Scenarios 2 and 3, respectively. In fact, a previous lifecycle-assessment study developed by Ramachandran et al. on the cogasification of sewage sludge mixed with wood waste for electricity production confirmed that negative GHG emissions can be achieved [50]. By comparing Scenarios 2 and 3, possible leakages of CH_4 during the methanation stage and the compression/liquefaction of bio-SNG may increase the potential for GHG release, eventually exceeding the total emissions of the hydrogen-production scenario. This hypothesis may occur because the global-warming potential of CH_4 is substantially higher when compared with CO_2 (28-times higher) [51]. Therefore, preventing CH_4 leakages in Scenario 3 would be an important task to limit the GHG emissions associated with the process.

Despite the expected good environmental performance offered by Scenario 1 (CHP option), the production of bio-SNG from sewage-sludge gasification is probably seen as the best approach to be deployed in Portugal, mainly due to the potential economic profits and direct connection with governmental energy strategies and policies. As reported before, the introduction of measures and technological solutions to minimize the impact of GHG emissions must be considered in order to maintain the attractiveness of this scenario.

Considering the industrial sewage-sludge-gasification plants currently in operation (mainly for heat and power production), which have feedstock processing capacities between 260 and 4200 kg/h wb (assuming an operating time of 7500 h/y), a processing scale of 2500 kg/h of sewage sludge may eventually be suitable for gasification plants to be deployed in Portugal [17,52]. In this scenario, about 19 plants would be required to process all the sewage sludge produced across the country, but this number would probably be lower when considering other competitive and mature alternatives for sewage-sludge valorization, such as anaerobic digestion with biogas/biomethane production.

5. Conclusions

Sewage sludges generated by WWTPs contain significant amounts of organic matter with interesting potential for conversion into useful energy and/or renewable gases through thermochemical processes. The present report assessed the potential of sewage-sludge gasification to generate added-value fuel products considering the following production scenarios: CHP, hydrogen, and bio-SNG. The quantification of sewage sludge for the calculations was based on information provided by wastewater-management entities located over the national territory and belonging to one of the most important groups operating at the national level: AdP-Águas de Portugal. The results of this report may be considered to evaluate potential market opportunities for products obtained from sludge gasification in Portugal. The main conclusions and remarks of this report are summarized below:

- Recent national legislation and action plans (e.g., Decree-Law 60/2020, EN-H2 and RNC 2050) promoting decarbonization and the use of sustainable technologies for waste-biomass conversion into energy and renewable gases may be seen as an important opportunity to facilitate the establishment of gasification plants in the upcoming years;
- Companies working in the wastewater sector are interested in the implementation of technologies focused on in-house energy production due to the large energy demands associated with treatment processes. The AdP group is responsible for the most important companies in the sector, and it therefore presents good potential for the development of projects aiming to design and integrate new solutions for sludge valorization;
- Hydrogen and bio-SNG production from renewable sources is still scarce across Portugal. Currently, the supply of both gases is mainly covered by using fossil resources or importing them from other countries. Recognizing the relevant role of renewable gases in various economic domains (transport sector, grid injection, and industry), and the importance of decentralized energy production from low-carbon sources in the coming years, sludge gasification appears as a possible solution for wastewater-management entities to comply with the climate policies;
- The possible routes to generate advanced fuel products from the producer gas obtained by gasification include the following: gas or steam engines/turbines for CHP, water–gas shift reactors coupled with PSA separation for hydrogen, and electrolysis + methanation followed by PSA separation for bio-SNG;
- Regarding the potential of the sludge produced by the considered upstream management entities, the yearly production of CHP, hydrogen, and bio-SNG were estimated at 28,523 MWh_e + 53,086 MWh_{th}, 1245 t, and 7436 t, respectively;

- The heat generated by CHP plant configurations may be used for sludge drying before gasification; however, centralized gasification units seem to be the best option to convert sludge into heat and power due to the lower amounts of feedstock available for a decentralized strategy;
- The energy content of the generated bio-SNG is greater than the energy derived from hydrogen or CHP, thus showing the interesting potential for investors in using bio-SNG for injection in existing grid lines or transportation;
- Considering the potential of dewatered sludges for energy or renewable-fuel production through gasification, there is a strong opportunity for the development of projects across Portugal to produce added-value products, helping to achieve the national and international targets of decarbonization, and to fulfill European policies regarding waste valorization. These services may be possibly directed to feasibility studies, project planning, and economic and lifecycle-assessment studies of centralized or decentralized gasification units that are able to process large or local amounts of sludge.

Concluding, the dewatered sludges produced by the Portuguese water-and-waste sector constitute a feedstock that may dynamize the energy and renewable-gas markets, creating new jobs and business opportunities that are waste-related. Gasification appears to be a feasible pathway to convert sludges into valuable products, considering an integrated concept in connection with the existing wastewater plants, favoring a circular economy and GHG abatement. This option is in line with recent government policies and legislation that may eventually result in the emergence of financial incentives.

Author Contributions: Conceptualization, O.A., B.G., G.L. and C.N.; methodology, O.A., B.G., G.L. and C.N.; validation, O.A., B.G. and B.R.; formal analysis, O.A., B.G., G.L. and C.N.; investigation, O.A., B.G., G.L. and C.N.; writing—original draft preparation, O.A.; writing—review and editing, G.L. and C.N.; visualization, O.A., B.G., B.R. and G.L.; supervision, C.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fundação para a Ciência e a Tecnologia, I.P. (Portuguese Foundation for Science and Technology), under the project UIDB/05064/2020 (VALORIZA—Research Centre for Endogenous Resource Valorization). The CoLAB BIOREF (Collaborative Laboratory for Biorefineries) also thanks the support of Fundação para a Ciência e a Tecnologia, I.P., and the Regional Operational Program of Alentejo (Alentejo2020) under Portugal 2020 (Operational Program for Competitiveness and Internationalization) for the grant ALT20–05–3559–FSE–000035.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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