



Can WWTPs Become Biorefinery Centers for Producing Green Hydrogen? A Simulation Case Integrating Sludge Gasification and Water Electrolyzers [†]

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Abstract

Wastewater treatment plants (WWTPs) can serve as hubs for converting waste into energy, thereby supporting a city's energy needs. Thermal processes, especially gasification, enable the transformation of sewage sludge into valuable products by producing energy-rich syngas for electricity generation. However, conventional air-based gasification introduces nitrogen as a diluent, reducing the syngas energy density. Integrating electrolyzers for hydrogen production into WWTP operations offers a strategic advantage: the oxygen co-produced during water electrolysis can be utilized as a gasification agent, thereby minimizing nitrogen dilution and enhancing syngas quality. The present work assesses the simulation of a conventional WWTP integrated with gasification and electrolysis systems using Superpro Designer V13. The results demonstrate that using pure oxygen in the gasification unit reduces the process's thermal energy requirements and increases the syngas energy content by 5.5% when operating in a CO₂ atmosphere at an equivalence ratio (ER) of 0.15. The integration of anaerobic digestion and sludge gasification improves the overall energy balance by increasing electrical output (67%) and enabling thermal energy recovery, allowing sludge drying without auxiliary fuel. Water electrolysis is integrated as an energy storage system, allowing flexible operation during periods of excess renewable electricity. However, a simplified balance of this strategy reveals negative economic results unless electricity prices are below 7.5 c€/kwh. This approach underscores the need for further research into the use of reclaimed water for hydrogen production, as well as improving process integration to reduce the energy and water footprints of technologies supporting the green transition.

Keywords: sludge gasification; waste valorization; hydrogen production; syngas; energy storage



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1. Introduction

Urban wastewater treatment is a critical component of modern infrastructure, with the conventional activated sludge process being the most widely used method for reducing organic load. This process generates sewage sludge, an unwanted by-product made up of organic and inorganic materials. Large plants use anaerobic digestion to stabilize sludge

and recover energy as biogas, whereas smaller plants usually apply aerobic stabilization. Both methods reduce volatile solids and lessen odor potential. When properly treated, sludge can be repurposed as an organic soil amendment, aiding in nutrient recycling and enhancing soil carbon content. In the European Union, approximately 40% of the sewage sludge generated is applied to agriculture, while landfilling still accounts for a considerable proportion of disposal practices (around 11%) [1]. This distribution highlights a significant opportunity to improve sludge valorization in line with bioeconomy principles, reducing greenhouse gas emissions and supporting the transition to waste-free resource management [2]. Moreover, when properly monitored and compliant with regulatory standards, the agronomic use of sewage sludge remains a safe and viable valorization pathway [3,4]. While nutrient cycling aligns with circular economy principles, concerns about the use of sewage sludge persist. This is particularly true when considering the risks posed by emerging contaminants and microplastics in sludge. For this reason, current legislation governing wastewater treatment and sludge management increasingly incorporates aspects regarding environmental protection, public health, climate-change impacts, and broader socio-economic implications [5]. The European wastewater treatment directive was updated to align with the Zero Pollution Action Plan, addressing the impacts of microplastics, pharmaceuticals, and cosmetics, as well as the high costs of their removal [6].

Municipal wastewater could irrigate and fertilize vast agricultural areas while producing biogas to power millions of households [7]. However, this potential is constrained by the need to remove micropollutants and control risks from heavy metals and persistent organic pollutants. Microplastics and pharmaceuticals in sewage sludge can harm soil health. When agricultural use is not feasible, thermochemical treatments are the best option for converting sewage sludge into energy or valuable products. Although incineration enables energy recovery, several other thermal technologies—such as pyrolysis, gasification, hydrothermal carbonization, wet oxidation, and supercritical water gasification—are also considered promising options for sludge valorization and contaminant removal [8,9]. Pyrolysis and gasification allow better process control by adjusting operating conditions to the feedstock. Pyrolysis generates bio-oil, biochar, and syngas rich in CH_4 , H_2 , and CO , but requires external heat because it lacks an oxidizing agent. Gasification, a more established option, can struggle with high-ash wastes. Gasification produces syngas as the main energy carrier and a carbon-rich residual ash that requires proper disposal. Introducing air or oxygen into the gasification process enables partial oxidation, making the operation autothermal. However, when air is used, nitrogen inevitably dilutes the syngas.

This study simulates the integration of a water electrolyzer in WWTPs as an energy-storage strategy. The oxygen co-produced during electrolysis is used as a gasifying agent to increase syngas energy density. The goal was to assess whether conventional wastewater treatment plants (WWTPs) can be transformed into renewable-energy hubs capable of storing surplus renewable electricity and thereby reducing instability in energy systems dominated by variable renewable sources. The novelty lies in the integrated application of sludge gasification and water electrolysis within WWTPs to enhance energy recovery and system flexibility. While the existing literature has explored sludge gasification as a pathway to produce syngas, challenges remain, including nitrogen dilution when air is used as the gasifying agent. The proposed approach not only avoids nitrogen dilution but also links wastewater treatment to renewable energy systems. The central objective is to evaluate whether conventional WWTPs can be transformed into renewable energy hubs that can store surplus renewable electricity and mitigate the variability of the energy supply from intermittent sources. Furthermore, the study advances existing research by simultaneously considering the combined use of reclaimed water, excess renewable

energy, and sludge gasification within a unified framework, thereby contributing to the development of more sustainable and resource-efficient wastewater treatment systems.

2. Materials and Methods

The WWTP model used in the present study was based on previous work [10–12]. The sewage sludge produced was estimated by SuperPro Designer V13. A treatment capacity of 150,000 equivalent inhabitants was assumed for the WWTP, and the main stages included: the primary settler, a conventional waste-activated sludge process, sludge digestion, and sludge dehydration and drying. The details of specific process assumptions were reported by González et al. [12]. The assumptions consider a specific wastewater production per inhabitant of 330 L/d [13], a biomass yield of 0.6 for the conventional WAS process, and 35% WAS recycling [12]. Methane-specific production for sludge was assumed to be 300 mL/g VS, based on the average values reported by Martínez et al. [14], Thorin et al. [15], and Song et al. [16]. Digestion conditions were simulated using a mesophilic regime (37 °C), a hydraulic retention time (HRT) of 21 days, and an inlet sludge temperature of 15 °C. 95% heat transfer efficiency and 5% heat losses were assumed to estimate digester thermal demand [11,12].

The combined heat and power (CHP) engine efficiency was 52% for thermal energy and 39.7% for electricity. About 50% of the thermal energy recovered from the engine was high-temperature thermal energy derived from combustion gases. An auxiliary burner was assumed to be part of the sludge-drying system, with 95% efficiency. A boiler for producing hot water at 80 °C was assumed to be part of the heating system needed to cover the digestion heat demand. The boiler efficiency was 80%, with a heat transfer efficiency of 90%. A Pinch analysis was performed to establish energy recovery options. Sludge characteristics are shown in Table 1. The values are averages from those reported by Mun et al. [17], Migliaccio et al. [18], and Akbari et al. [19].

Table 1. Assumptions for sewage sludge characteristics. Mean values from those reported in the literature [17–19].

Parameter	Value
Volatiles (%)	61.6 ± 6.6
Ash (%)	33.9 ± 3.1
LHV ¹ (MJ/kg)	12.4 ± 0.8
Elemental composition (%)	
C	34.0 ± 1.2
H	5.2 ± 0.4
N	4.7 ± 0.6
S	0.7 ± 0.1

¹ LHV: Lower heating value.

The digested sludge was dehydrated using horizontal decanter centrifuges. The dehydrated slurry had a total solid content of 27%. The drying process was designed to achieve a moisture content of 20% [11]. The gasification-based scenario was assessed at an equivalence ratio (ER) of 20% with air as the gasifying agent. A fluidized bed gasifier was assumed in the simulation. The gasification temperature was in the range of 720–750 °C. The gasification temperature was in the range of 720–750 °C. The gasification temperature was determined using equilibrium equations, with the incoming material set to 780 °C and adiabatic conditions assumed. Carbon conversion was set at 85%. Gasification equipment thermal losses were 5% [11]. Thermal energy was recovered from the hot syngas stream to meet part of the gasifier’s preheating requirements and to reach the gasification temperature. The process was simulated at ERs of 0.15, 0.2, and 0.25, using different

gasifying agents: air, combustion gases from the CHP unit under conditions equivalent to air gasification, and an oxygen-enriched atmosphere. In cases where carbon dioxide (CO₂) was used as the gasifying agent, oxygen was produced by water electrolysis. The energy requirements for sustaining the gasification process were assessed in two different scenarios: the minimum energy demand, which accounted for 2.5% of the gasification products, and the maximum energy demand, which assumed 30% of the gasification products. The electrolyzer specific energy demand was 4.3 kWh/m³ of H₂ [20,21]. The energy demand to obtain water quality suitable for electrolyzer use from treated wastewater was estimated at 1.6–2.5 kWh/m³ of residual water, assuming a treatment train comprising filtration, reverse osmosis, and polishing [22,23].

3. Results and Discussions

The model estimated a sludge production of 10.1 m³/h, a mixture of primary and secondary sludge. The secondary sludge represented 58% of the sludge stream. Based on previous estimates, the amount of biogas produced was enough to cover the digestion heat demand when using a CHP engine [11]. However, when drying sludge, auxiliary fuel is required to meet the additional energy demand. Figure 1 schematizes the system configuration, assuming the total biogas is used in the CHP unit, resulting in an electricity production of 430 kW. About 50% of the thermal heat recovered by the engine is considered to be low-temperature heat, suitable for meeting digester needs but not for sludge-drying demand.

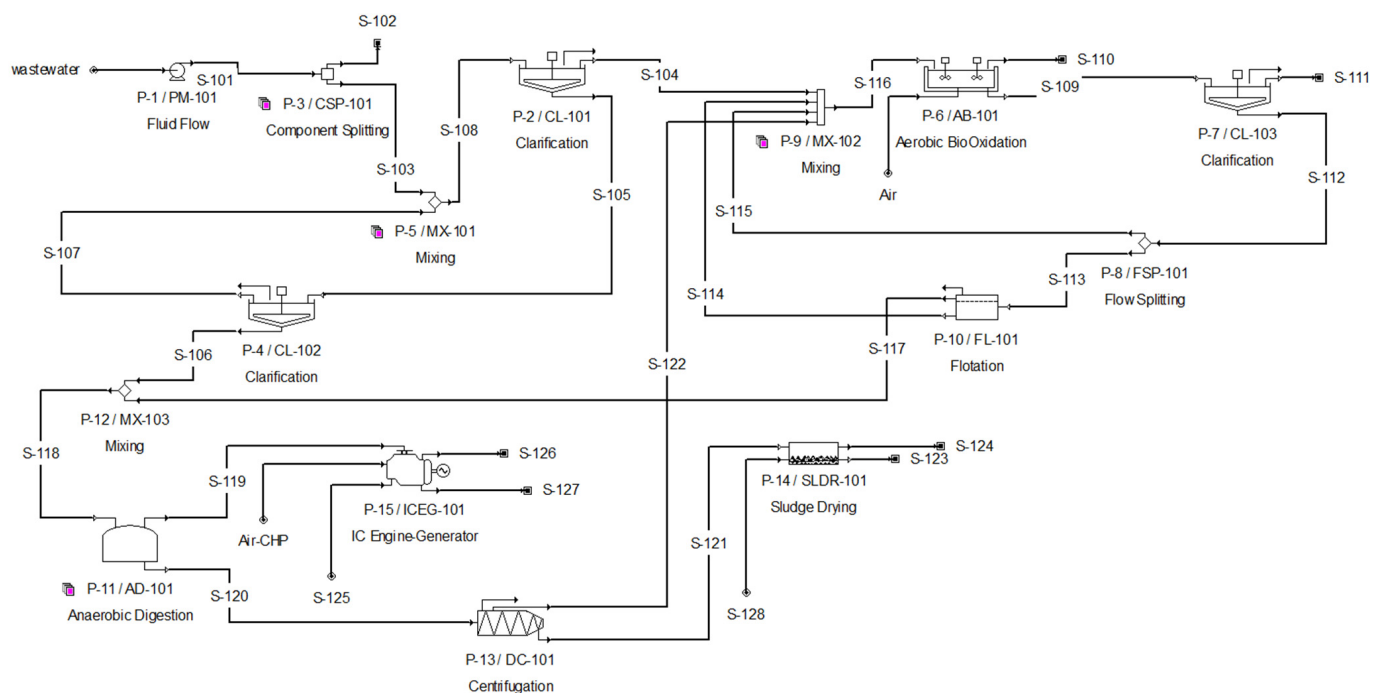


Figure 1. Schematization of the conventional WWTP where sludge digestion and drying is considered.

Figure 2 shows the values of the different power categories obtained from the simulation. Biogas is valorized in a CHP engine, obtaining electricity and heat. The thermal energy derived from the process is sufficient to meet the digester's demand for maintaining the process temperature but is not enough to cover the thermal energy required for drying sludge. This result is in accordance with Ochieng et al. [24], who also evaluated this type of configuration, thus requiring additional fuel to achieve sludge drying.

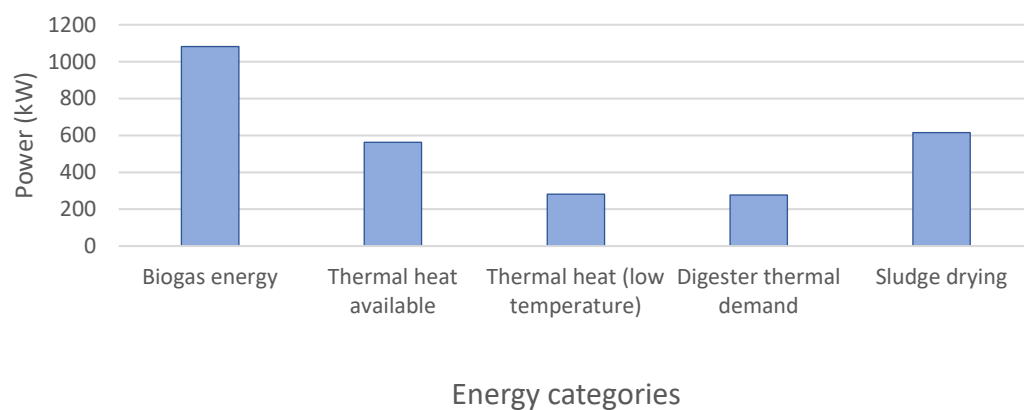
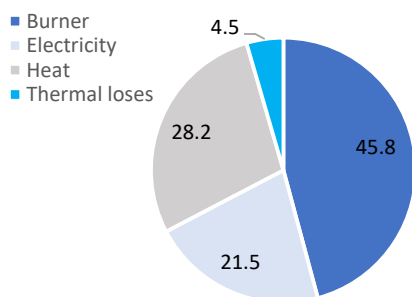
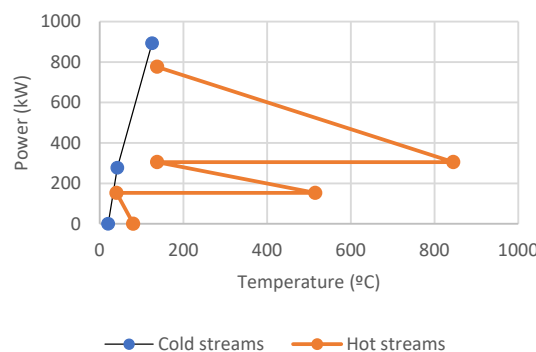


Figure 2. Power estimation based on energy availability of the plant configuration by assuming full valorization of biogas in a CHP engine.

Figure 3 shows the distribution (expressed as a percentage) of the power in biogas and the results of the Pinch analysis for the process. The drying unit requires 616.2 kW, which is to be supplied by combustion gases derived from either the engine or a gas burner. In the present case, the available heat accounts for only 45.8%. Therefore, some of the biogas is diverted to a burner to produce additional heat, at the expense of reduced electricity production. The engine's output decreases to 233 kW, thereby reducing the available heat to meet the digester's thermal needs. Auxiliary fuel is then required to meet the boiler's energy needs for digestion, resulting in the use of additional methane (natural gas). The heat generated by the engine and available for digestion (as hot water) amounts to 152.5 kW. The estimated natural gas flow required to compensate for the drop in thermal energy is 418 m³/d (173 kW).



(a)



(b)

Figure 3. (a) Distribution of biogas power to cover sludge drying demand. (b) Pinch analysis diagram of cold and hot streams available in the process.

3.1. Results from Sludge Gasification Simulation

Figure 4a shows the schematic representation of the gasification unit integrated in the sludge line. The operation that demands the most energy is sludge drying. In the present case, the energy contained in the sludge amounts to 1010 kW based on the LHV of sludge. The sludge stream obtained after the digestion process undergoes dehydration and subsequent drying, resulting in a moisture content of 20% (based on model assumptions reported in González et al. [11,12]).

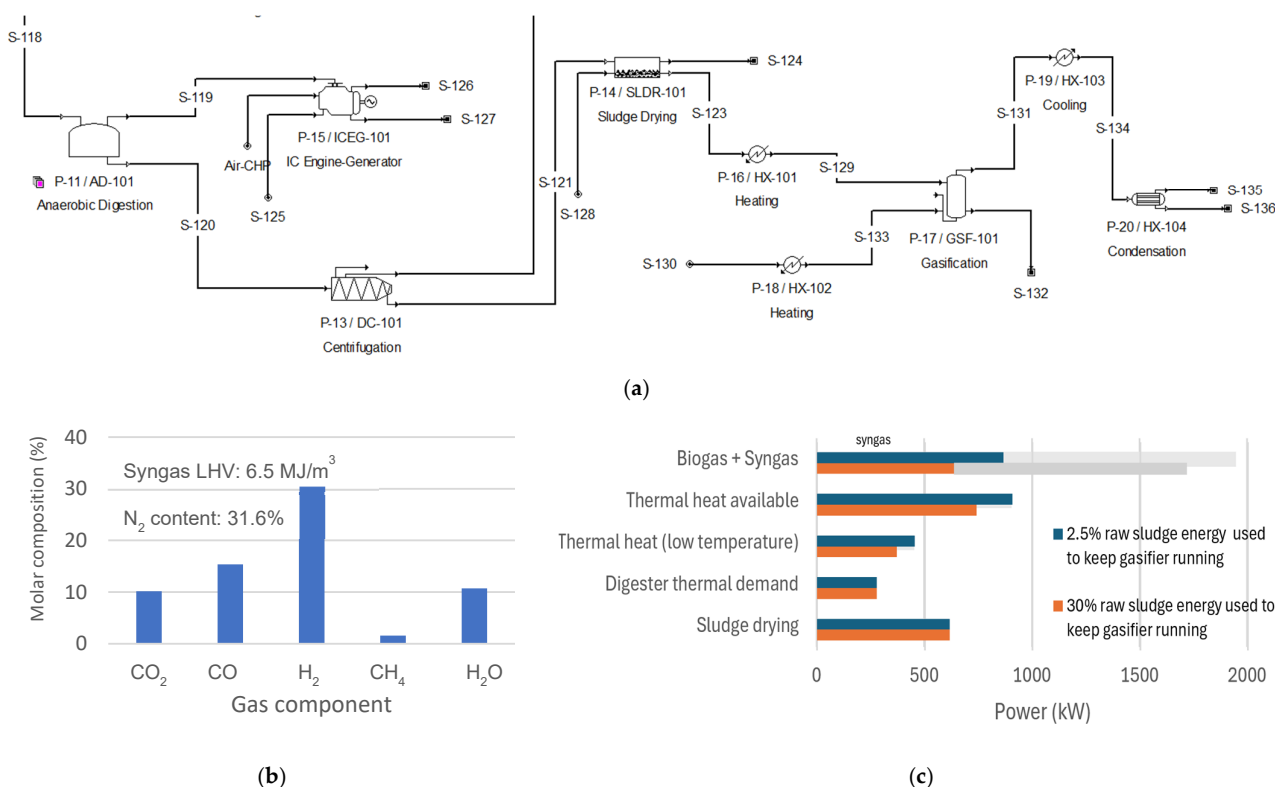


Figure 4. (a) Schematization of sludge gasification using air as gasifying agent. (b) Syngas characteristics (values obtained from simulation at ER: 0.2). (c) Results from the energy balance derived from the integrated process (digestion–gasification) by considering the minimum (2.5% of dried sludge energy) and maximum (30% of dried sludge energy) amount of energy required for operating the gasification unit.

Simulation results at an ER of 0.2 are represented in Figure 4b. The high moisture content of sludge raises the gasifier's heat demand, but some energy can be recovered from the enthalpy of the high-temperature syngas stream and the chemical energy of H₂. The energy required to maintain gasification at 740 °C is approximately 2.5% of the energy contained in sludge. Increasing the energy demand for the gasification process by 30% reduces the energy available in the syngas stream by almost the same amount (28.2%), thereby affecting electricity production if both fuel streams (biogas and syngas) are valorized in the CHP engine. Figure 4c shows the results from the global energy balance. The auxiliary burner meets the gasifier's thermal demand, eliminating the need for natural gas by using the available syngas. With the minimum gasifier energy demand, only 10% of the syngas must be diverted to the auxiliary burner, allowing electricity production to reach 718 kW—much higher than the 430 kW obtained when using only biogas. When 30% of the sludge energy is required for gasification, 16.4% of the syngas is diverted to the burner, reducing electricity generation by 19.7%.

Varying the ER alters the operating gasification temperature and gas composition. Reducing the ER to 15% decreases the temperature to 648 °C (under adiabatic assumptions). The decrease in temperature (92 °C) leads to greater production of CH₄ and H₂. By contrast, an ER increase causes syngas dilution by nitrogen and reduces the fraction of CH₄ and H₂ (see Figure 5a). The increase in CO composition is due to higher operating temperatures attained when more air is added, which affects the balance via the Boudouard reaction [25,26]. The separation between the heating stage and subsequent gasification results in temperature changes when operating under adiabatic model conditions (Figure 5a).

However, when considering a constant temperature of 740 °C across all ER values, the CO₂ levels increase with greater air availability, while CO and H₂ decrease (see Figure 5b).

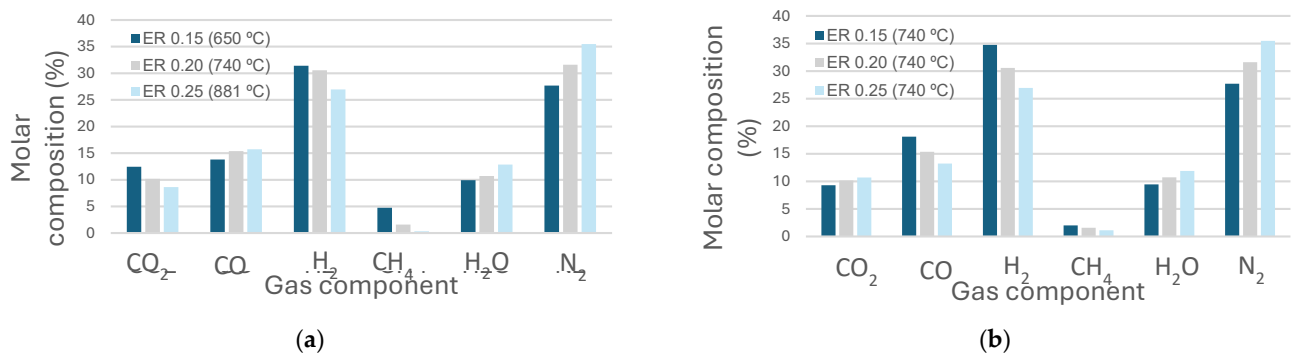


Figure 5. (a) Gas composition obtained at different ER, assuming adiabatic conditions for model estimations. (b) Gas composition obtained at different ER assuming, in this case, a constant gasification temperature of 740 °C.

3.2. Results of Sludge Gasification Simulation Under Oxygen Enrichment

Figure 6 represents the sludge line section incorporating an H_2 electrolyzer and engine gas recycling. The introduction of a water electrolyzer for H_2 production also results in a pure stream of O_2 . The O_2 can replace the air required by the gasifier, thereby reducing nitrogen dilution. The electrolyzer is set to produce the same amount of O_2 needed to operate the gasifier, with an ER of 0.2, using an equivalent mass of gasifying agent and replacing the inert components with exhaust gases recirculated from the engine.

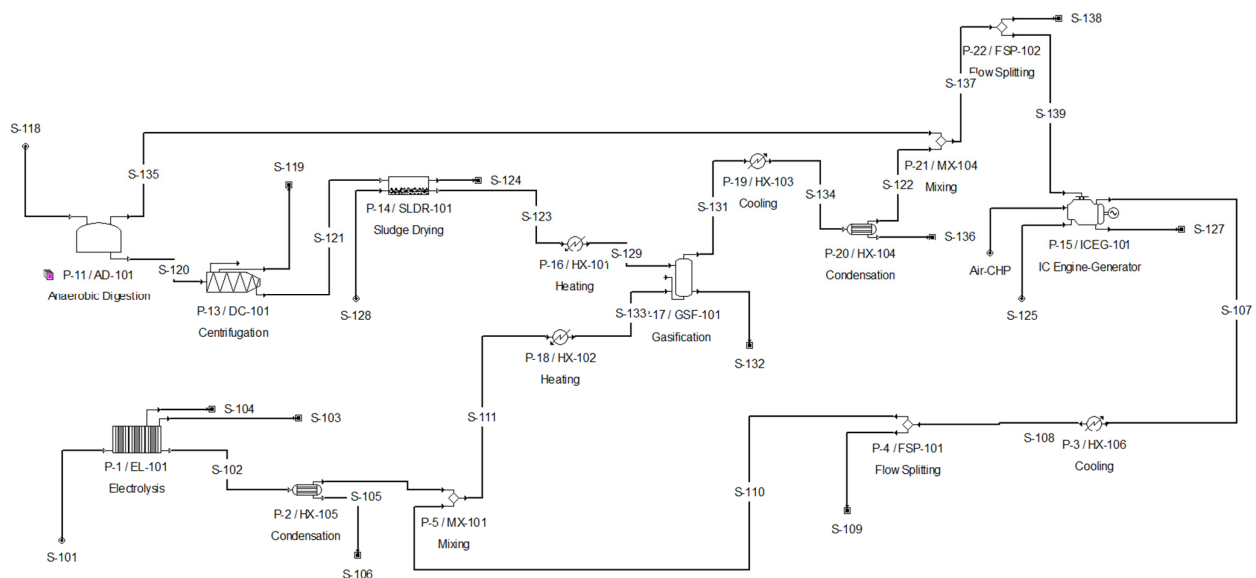


Figure 6. Schematic representation of the sludge line including H₂ production from water electrolyzers.

Replacing the nitrogen atmosphere with recycled gases has no effect on energetic gases, affecting only the composition of the inert components. Because the recycled exhaust gases contain less nitrogen, the syngas LHV rises from 6.5 to 7.0 MJ/m³, even though the overall energy content of the stream remains unchanged. O₂ enrichment was achieved in this case by using an electrolyzer. Increasing the ER from 0.2 to 0.25 results in a higher operating temperature. In the first case, the temperature was 740 °C, which increased to 880 °C upon oxygen enrichment under the same operating conditions (see Figure 7). However, no benefits were observed regarding gasification performance. Syngas had a

lower heating value (LHV) of 7.0 MJ/m^3 , resulting in a total energy content of the gaseous stream of 897 kW, which represents a 6% decrease. These results are consistent with those reported by Ismail et al. [27] for agricultural waste tested in a fluidized-bed gasifier. These authors noted that O_2 enrichment increased the temperature, thereby affecting the levels of CO and H_2 produced.

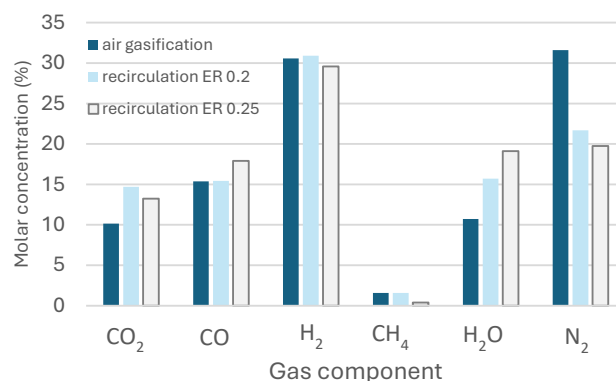


Figure 7. Syngas composition derived from model simulation under air and CHP-recirculation gases.

The integration of an electrolyzer significantly increases energy demand, rising from 206.7 kW at ER: 0.2 to 261.8 kW at ER: 0.25. Although some of this energy was recovered as hydrogen, no improvement in gasification performance was observed. Moreover, using treated wastewater as the electrolyzer feed to produce ultrapure water imposes an additional treatment train—including filtration, reverse osmosis, polishing, and degassing—which is estimated to consume 2 kWh per m^3 of water (based on the range indicated in the Materials and Methods Section 2). The use of reclaimed water adds 222.85 kW of power demand. A significant increase in power is required for this approach to be implemented. Using excess renewable energy can be considered a suitable option to meet the additional energy required for this configuration. However, intermittency is the main characteristic of renewable energy systems when based on wind turbines and photovoltaic cells. H_2 production can be considered a strategy for energy storage, thereby reducing uncertainty as a country's energy mix increases the share of renewable energy. In the Spanish case, the installed power for electricity production amounts to 150,809 MW, but the mean power demand is just 29,224 MW [28]. Using surplus power to produce and store hydrogen (H_2) can help stabilize the energy system and prevent curtailment or negative electricity prices. In this case, 130 kW could be stored at an ER of 0.2 and 165 kW at an ER of 0.25, corresponding to an energy recovery of 62%. However, this potential is significantly diminished when accounting for the energy required to treat reclaimed water, reducing the effective H_2 storage capacity to 30%.

Using pure oxygen can increase syngas energy density by replacing nitrogen, but this benefit is lost when a CHP unit is used, since the energy contained in syngas would be the same. However, the gasification reactor can operate as a CO_2 trapping unit, using CaO as the bed material. The use of CaO as both a catalyst and a CO_2 -capturing compound has been proposed by Wei et al. [29]. The process consists of creating a circulating moving bed in which CaO absorbs CO_2 during the gasification stage (an exothermic reaction). Then, in the second stage, CaCO_3 is calcined (heated), releasing the previously captured CO_2 . CaO also acts as a catalyst, enhancing H_2 formation upon steam addition and facilitating tar-cracking reactions [30,31].

Using an O_2 – CO_2 gasifying mixture enables in situ CO_2 capture, removing inert gases and increasing syngas energy density by boosting CO and CH_4 across the ER range tested. When considering CO_2 as a gasifying agent, the volumetric proportion of CO_2 used to

fluidize the bed is lower due to its greater mass. This issue translates into operational benefits, including a lower gas volume pumped and changes in operating temperature under adiabatic conditions due to its higher specific heat capacity. The greatest benefits were obtained for the cases with ER values of 0.15 and 0.2, which produced a greater volume of CO and CH₄ (see Figure 8a). Figure 8b shows the estimated power for the syngas stream when gasification is performed in a CO₂ atmosphere. Reducing the amount of oxygen available to reach an ER of 0.15 represented a 5.5% improvement in the syngas energy content compared with the gasification-based case scenario (air gasification with an ER of 0.2). In contrast, applying the same ER value yielded a smaller improvement (2.4%).

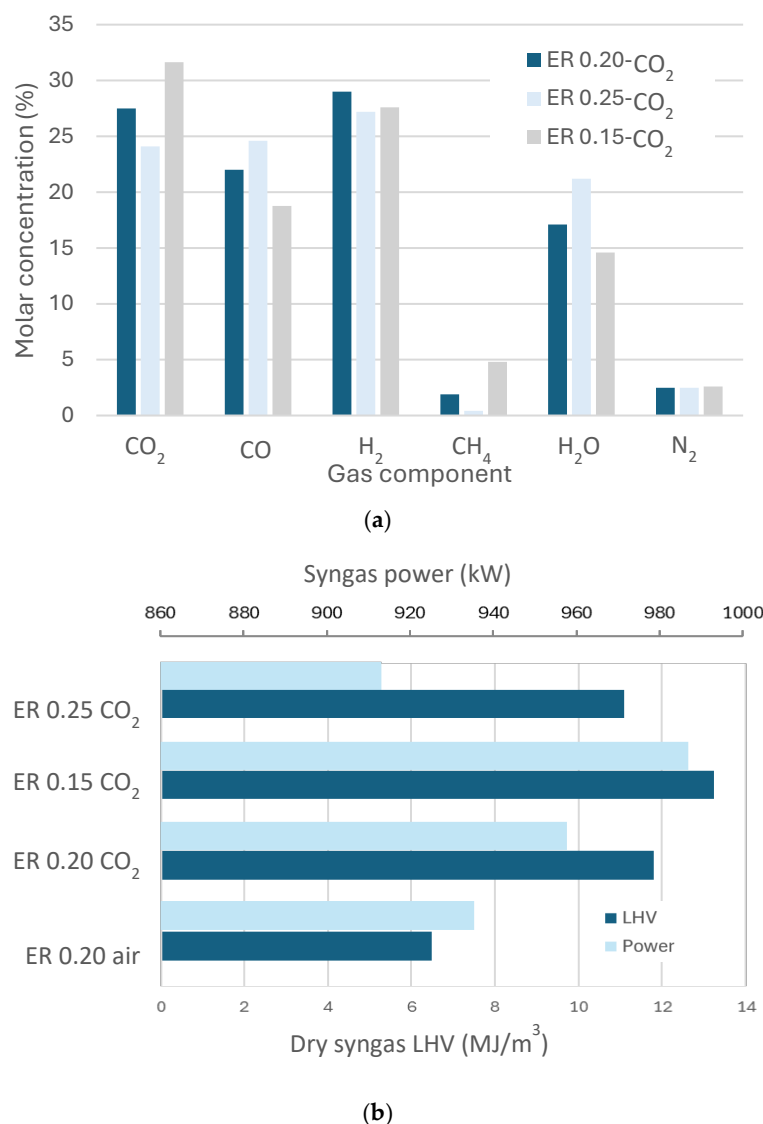


Figure 8. (a) Syngas composition and (b) syngas LHV and power obtained under CO₂ atmosphere and varying ERs.

3.3. Effect of Electricity Prices on the Economic Balance

The hydrogen (H₂) produced by the electrolyzer is considered green hydrogen because it is generated using electricity from renewable energy sources. A preliminary balance, considering only an H₂ selling price of 5.85 €/kg [32] and an electricity price of 0.13 €/kWh, would yield a negative economic balance due to the high energy demand of the electrolyzer and the water-treatment train for generating ultrapure water from treated wastewater. Figure 9 represents the electricity production costs and revenues obtained from selling H₂

over a range of 2 to 20 c€/kWh for the electricity price. Efficiencies of water electrolyzers and water reclamation technologies are expected to increase, thereby also improving the energetic balance of this approach. Despite considering efficiency improvements of up to 40%, setting the same selling price for H₂ gas would require an electricity price below 9 c€/kWh to achieve a positive economic balance. Increasing this selling price by 20% or even 40% would not reach a positive balance for the base case. The base-case assumptions would require an electricity price below 7.5 c€/kWh, even with a 40% increase in the H₂ selling price.

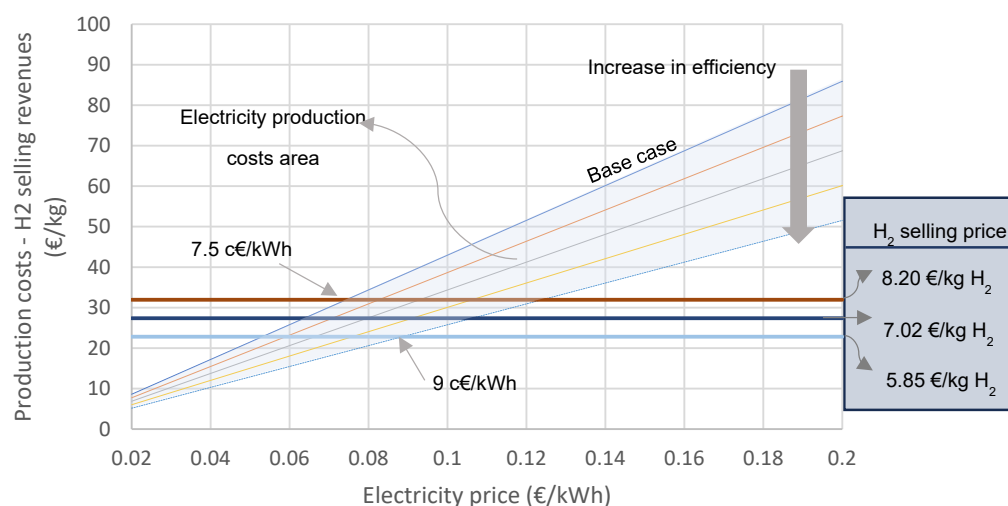


Figure 9. H₂ electricity production costs and selling revenues estimated for the base case (53 kWh/kg H₂ and 2 kWh/m³-treated water).

Water electrolysis is recognized as a key technology player in the landscape of a decarbonized energy mix. This technology, although it requires efficiency improvements and raises concerns about water use in water-scarce areas, can play a significant role as an energy storage alternative or for producing fuels for hard-to-electrify sectors. The use of treated wastewater to produce ultrapure water, although it significantly increases production costs, may serve as an inflection point for this technology to obtain the highly valued H₂ gas sustainably. There is also an additional benefit in the support it can offer for grid stability and the smooth integration of variable renewables. This strategic role is explicitly embedded in the European Union’s climate framework, under the updated Renewable Energy Directive (RED III) [33]. This directive defines renewable hydrogen as a “renewable fuel of non-biological origin” (RFNBO) when produced via electrolysis powered by renewable electricity. Complementing this directive, the European Union established the EU Hydrogen Strategy under the European Green Deal, and the REPowerEU Plan [34]. This regulatory framework demonstrates the relevance of H₂ production in the future decarbonized economy. In this regard, water electrolysis is not only a technological pathway for green hydrogen production, but also a cornerstone of EU policy to achieve climate neutrality. The integration proposed here brings the aim of transforming WWTPs into energy hubs that can enhance renewable energy penetration and formalize energy storage within the internal energy market closer.

4. Conclusions

This study highlights the potential of integrating water electrolysis into wastewater treatment plants (WWTPs), transforming them into renewable energy hubs. Using the oxygen produced during electrolysis as a gasification agent yields a 5.5% increase in the energy content of syngas from sewage sludge gasification. The process integration

proposed also reduces the thermal energy requirements of the overall digestion–gasification configuration, allowing for sludge drying without the use of auxiliary fuel. This innovative strategy allows WWTPs to contribute to local energy needs, particularly during peaks in renewable electricity generation, thereby promoting a circular economy. However, challenges remain in using treated wastewater as a source for the electrolysis unit, due to the high energy costs associated with these operations. The economic balance, considering only electricity costs and the H₂ selling price, is negative under the current scenario. Increasing the efficiency of electrolyzers and wastewater treatment is essential to enable the integration of this technology into WWTPs and to transform these treatment centers into energy-storage hubs that can serve as essential infrastructure for stabilizing the energy grid and facilitating renewable energy penetration.

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