Towards energy security by promoting circular economy: a holistic approach

Manuel Taifouris[a], Mariano Martín[a,*]

[a]*Department of Chemical Engineering, University of Salamanca, Plza. Caídos 1-5, 37008 Salamanca, Spain*

Abstract

Dependence on fossil fuels, coupled with continuous supply disruptions by the most important natural gas suppliers, has jeopardized the energy security of most European countries. Therefore, determining the regions that can significantly increase their natural gas independence through the circular economy of their wastes is more important than ever. This work presents a multi-scale analysis to determine the possibility of implementing a circular economy toward reducing the regions dependency on fossil natural gas. A holistic approach is used to evaluate the availability of waste (manure, municipal solid waste, sludge, and lignocellulosic waste) and model the waste treatment processes (gasification and anaerobic digestion), together with a techno-economy analysis of the infrastructure required. A facility location problem optimizes the selection of the technology, the production capacity and the location of the facilities, according to the available budget. The analysis is focused on Spain, where, at the national level, an investment of 9458 M€ and an operating cost of 5000 M€ per year would allow covering 35% of the natural gas demanded. However, the regional analysis shows that a total of 19 provinces can be self-sufficient with this budget. These provinces have a high biomethane production potential through lignocellulosic waste gasification and a low demand for natural gas. Since energy is a basic commodity, the ability to produce enough biomethane to cover the entire demand for natural gas gives waste valorization strategic importance at both the social and economic levels.

Keywords: Agricultural residues, Sustainable process design, Natural gas, Circular economy

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[*] Corresponding author

Email address: `mariano.m3@usal.es` (Mariano Martín)

1. Introduction

Notwithstanding the fact that significant efforts have been made to promote decarbonization policies among European countries (European Comision, 2018), the current dependency on fossil fuels (Martins et al., 2018), their distribution (Economides and Wood, 2009), together with potential supply disruptions of the most important suppliers of natural gas, put the energy security of most countries of the European Union at risk (Mišík, 2022). Although this risk can be reduced through a robust natural gas supply chain design (Urciuoli et al., 2014), this does not eliminate the need to import natural gas from other countries, reducing the European energy independence (Mišík, 2022).

The growing world population has led to more intensive food production systems (crops, meat, and milk, among others) (Cordeiro et al., 2022), creating areas of high organic waste production. Animal wastes, such as manure, can cause nutrient pollution, leading to the eutrophication of water bodies and soil deterioration if they are not properly treated (Menzi et al., 2009). Besides, in densely populated areas, where the production of municipal solid waste (MSW) and sludge is an issue, the treatment of this waste is quite inefficient, with 23% ending up in landfill and 26% being incinerated, losing a large part of its value (European Comision, 2021).

Both problems can be solved simultaneously by following the principles of the circular economy of the waste. Technologies such as anaerobic digestion (León and Martín, 2016) of wet waste (e.g. manure, MSW or sludge) or gasification (Sánchez et al., 2019) of dry residues (lignocellulosic waste) can provide the means to address the issue. In this context, there is a wide variety of studies focused on analyzing the biomethane production potential in different countries, such as United States (Wang et al., 2018) and Chile (Bidart et al., 2013). These studies make it possible not only to determine in which areas it is more efficient to direct waste treatment to biomethane production but also to find which of these areas can be energetically independent. This potential energy independence is an important incentive for waste treatment, due to the possibility of creating decentralized networks independent of the main pipelines (Smyth et al., 2011). This guarantees the availability of sufficient biomethane in those regions regardless of disruptions from foreign suppliers. However, most of these studies use empirical yields that directly relate biomethane production potential of a region to the number of animals, crops or people from which the residues are derived. This approach completely decouples the estimation of the amount and composition of biomethane from the transformation process and the specific composition of each waste. On the one hand, the composition of animal waste strongly depends on the feed, breed, sex, and age of the animals, which leads to large variability in the waste composition (Council, 2000). Moreover, the amount and composition of biomethane depend directly on the carbohydrate, lipid, and protein content of these wastes (Angelidaki et al., 1999). This makes it very inaccurate to estimate a biomethane production potential only considering the type of animal. On the other hand, the design of the process depends on the amount and composition of the waste, modifying the design of the equipment (size and type of equipment), as well as the production and composition of products, affecting both the economic and environmental evaluation of the process (Taifouris and Martín, 2018). Finally, the facilities must be located close to the areas where the waste is produced, due to the high economic and environmental costs associated with waste transportation (Makara and Kowalski, 2018).

A multi-scale approach allows addressing the different scales of the production system, such as physicochemical characterization of the raw material, product and process design, as well as network design and distribution, through the use of principal engineering components, such as modeling, design, synthesis, simulation, and optimization (Floudas et al., 2016). Some authors have used this approach to analyze renewable energy storage (Heras and Martín, 2021) or integrated livestock and crop management systems (Taifouris and Martín, 2022). It allows not only the adaptation of the treatment processes to the properties and amount of the waste but also the location of the facilities. This approach optimizes the treatment processes for specific cases, reducing the cost of biomethane production, as well as allowing the integration of energy between the different stages of the process. However, despite the wide variety of studies about the use of waste to produce biogas (Weiland, 2009), to the best of the authors' knowledge, there is no study that uses this holistic approach to analyze the application of the circular economy in reducing the country's dependence on fossil natural gas, as well as its operational and investment costs, the best location and size of the treatment facilities, and the optimal waste management budget.

Therefore, this work presents a study, which integrates a series of mathematical optimization models to determine, from a reduced number of parameters available in public databases, the amount of biomethane that different agricultural districts in Spain can produce from their wastes. This framework provides information on the optimal selection of treatment plants (size and type of waste treated), their location, the investment and operational costs, the production cost of the methane generated, and the percentage of consumption of CH_4 that can be covered by the biomethane produced by these factories. The main variable is the waste management budget. The rest of the document is organized as follows. Section 2 presents the optimization framework used to perform the proposed analysis, including a description of the problem, the procedure to estimate the amount of waste produced, the description of the processes considered to treat the waste, as well as, an explanation of the techno-economic analysis performed and the facility location problem. In Section 3, the model is applied to Spain, and the results are shown. Finally, in Section 4, the conclusions are presented.

2. Framework development

To approach this study from a holistic point of view, it is necessary to consider the estimation of the amount and composition of the waste, the design of the treatment processes (both gasification and anaerobic digestion), together with the economic evaluation of its scale-up, the optimal selection of the location and size of the facilities.

First, the framework starts by dividing the country into spatial units (provinces, counties, etc.). From the information corresponding to animal population (number of animals and their age), cultivated area, and population in each spatial unit, it is possible to estimate the amount of waste generated. Next, by modeling the gasification and anaerobic digestion processes, it is possible to establish the amount and composition of biomethane that can be produced from the composition of each of the wastes and the operating conditions of the processes. In addition, both investment and operating costs can be determined through the design of the equipment that conforms the processes. This modeling aims at determining the operating conditions to minimize the cost of biomethane production, establishing the relationship between treatment capacity, capital invested, operational costs, and biomethane produced. Since biomethane is to be injected into the country's gas installations, it is necessary that this gas complies with the technical specifications required by the country's regulations. Finally, based on the results of the previous step, a facility location problem searches for the size, type, and location of the facility that maximizes the total biomethane production for a specific budget.

2.1. Estimation of the production and composition of waste

To estimate waste production, different procedures are followed depending on the nature of the waste:

- Lignocellulosic waste: This residue is estimated from the amount and type of crops grown per year. The amount of residue grown by the type of crop can be consulted in Table 1. It is considered that all the waste generated is available to produce biomethane.

- Manure: The amount of manure is estimated from the number of animals and their age. 22 t/y of manure are generated by cows and calves with ages higher than 24 months, 19 t/y by calves with ages between 12 and 24 months, and 11 t/y by calves with age lower than 12 months (Merino, 2006).

- MSW and Sludge: The amount of these wastes is estimated based on the number of inhabitants of cities with a population of more than 50,000 ha. 388 kg (INE, 2019) of MSW and 105 kg (Bianchini et al., 2016) of sludge are generated per inhabitant and year in Spain.

Table 1: Lignocellulosic residues from crops (García-Condado et al., 2019)

Crop	**Residue yield (t/ha)**
Maize	8.9
Sorghum	6.4
Wheat	5.9
Rye	4.7
Oats	4.1
Barley	4.0

The most common compositions of theses residues from the literature are used, which can be consulted in Tables 2 and 3. In the case of lignocellulosic residues, an average composition has been

Table 2: Composition of the wet wastes (Kafle and Chen, 2016; Park et al., 2016; Liew et al., 2022; Li et al., 2021; Alibardi and Cossu, 2015; Nielfa et al., 2015) (RM: raw material)

Waste	**Manure**	**MSW**	**Sludge**
Unit	g/kgRM		
Lipids	0.880	1.501	0.333
Carbohydrates	17.435	38.766	2.057
Protein	3.1988	13.740	2.856
Total Solids	220	140	170
Volatile Solids	204.600	93.800	93.500
Total Nitrogen	0.229	1.159	0.144
Organic Nitrogen	0.114	0.062	0.043
Phosphorous	0.097	0.169	0.124
Potasium	0.620	0.620	0.620

used among the different types of residues that can be generated in crop management, since the composition varies very little from one to another. These compositions can be updated through specific studies to increase the accuracy of the estimates.

Table 3: Ultimate analysis of the lignocellulosic waste (Wilen et al., 1996)

Component	wt% d.b.
C	47.640
H	5.835
N	0.546
S	0.106
O	41.920
Ash	3.953

2.2. Process analysis and design

In this section, the processes considered for waste treatment, the gasification of dry waste (i.e. lignocellulosic waste), and the anaerobic digestion of wet waste (i.e. manure, MSW, and sludge) are modeled. In addition, a techno-economic analysis is performed, considering 50 different waste treatment capacities for each of the wastes considered. The designs are optimized to minimize methane production costs using a non-linear program (NLP).

2.2.1. *Gasificacion of the biomass*

A gasification process is used for the lignocellulosic waste treatment, due to the low water content of this type of waste. The modeling of the gasification, syngas upgrading, methane production, and biomethane upgrading are based on a first principles approach, such as mass and energy balances, thermodynamic equilibrium, and empirical correlations. While a more detailed explanation of the process model is shown in the supplementary material, the most important considerations are presented below. The flowchart of the process can be seen in Figure 1.

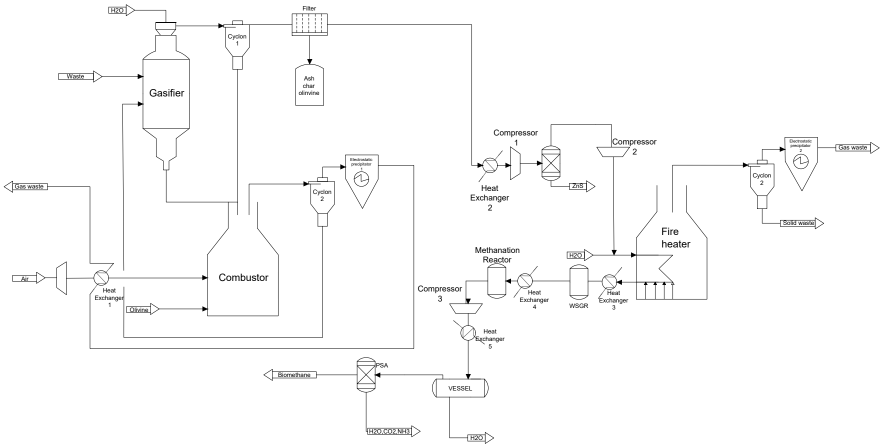


Figure 1: Flowchart of the biomethane production process through gasification

Following the results of Sánchez et al. (2019), the most profitable configuration is the indirect gasification system, which consists of a combination of a gasifier and a combustor (see Figure 1). In this type of system, the heat required for gasification is supplied by the combustion of the char formed by the gasification process (Blasi, 2004). Olivine is used as a heat transfer media (HTM) to transfer the thermal energy generated in the combustion of the char to provide the energy required for the endothermic reactions at the gasifier. In the combustor, the total combustion of all compounds is considered to perform the mass and energy balances, as well as to estimate the final temperature of this process. The composition of the syngas is estimated from the gasification temperature following the correlations of Phillips et al. (2007).

Regarding syngas upgrading, cyclones are used to separate the olivine and char. A steam reforming reactor is used to transform the hydrocarbons formed in the gasification into hydrogen. Next, a bed of ZnO is used to remove the hydrogen sulfide, with a yield of 100% (León and Martín, 2016), following the reaction presented in Eq.(1).

$$ZnO + H_2S \rightarrow H_2O + ZnS \tag{1}$$

While the cyclones and the bed of ZnO are modeled using empirical yields, the steam reforming system is modeled from the thermodynamic equilibrium conditions (Roh et al., 2010) of the two main reactions (i.e methane decomposition and the water gas shift reaction). All hydrocarbons, except for methane, are completely transformed into H_2 and CO (Aasberg-Petersen et al., 2003), following the Eq.(2). The amount of the rest of products and raw materials are estimated following Eqs.(3) and (4).

$$C_nH_m + nH2O \rightarrow nCO + \left(n + \frac{m}{2}\right) H_2 \tag{2}$$

$$3H_2 + CO \overset{kp1}{\leftrightarrows} H_2O + CH_4 \tag{3}$$

$$CO + H_2O \overset{kp2}{\leftrightarrows} H_2 + CO_2 \tag{4}$$

The furnace is considered as adiabatic. Subsequently, a water gas shift reactor (WGSR) is used to adjust the H_2/CO molar ratio to the optimal value for methane production in the next reactor. Equilibrium models (Roh et al., 2010) are used to relate the reaction temperature to the composition of the syngas. WGSR is also considered adiabatic. After the WGSR, an isothermal methanation (Duret et al., 2005) is used which is also modeled using mass and energy balances and thermodynamic equilibrium models (Roh et al., 2010). This reactor cannot exceed 773 K to avoid catalyst damage (Appl, 1999). Finally, a PSA system is considered to reduce the CO_2 content down to 2%, and completely remove NH_3 and water (León and Martín, 2016). This is necessary to make biomethane suitable for supply to the pipeline.

The detailed explanation of this process, together with the balances of mass, energy, and thermodynamic equilibrium, are shown in the supplementary material.

2.2.2. Anaerobic digestion of the biomass

An anaerobic digestion system is proposed to process the wastes with high water content. It is based on the work of León and Martín (2016), and Taifouris and Martín (2018). Since the model of León and Martín (2016) is not general enough to be applied to 3 different types of waste (manure, MSW, and sludge), it is necessary to develop a new model that combines both works. The flowchart of the process can be seen in Figure 2.

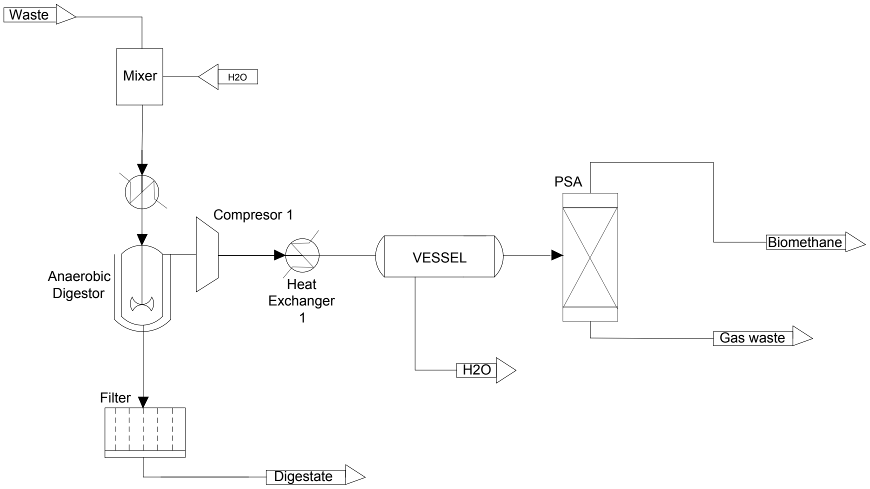


Figure 2: Flowchart of the biomethane production process through anaerobic digestion

León and Martín (2016) model requires information on the amount and composition of biogas that can be obtained from a specific waste. This information is provided by the model of Taifouris and Martín (2018) from the composition of the residues (carbohydrate, lipid, and protein fractions) using stoichiometric relationships, empirical yields, and biodegradability. The reactions of degradation of the lipids ($C_{57}H_{104}O_6$) , carbohydrates ($C_6H_{10}O_5$), and proteins ($CH_{2.03}O_{0.6}N_{0.3}S_{0.001}$) are shown by Eqs. (5), (6) and (7), respectively. $C_5H_7NO_2$ is the empirical formula of cell mass.

$$C_{57}H_{104}O_6 + 23.64H_2O + 1.4534NH_3 \rightarrow 36.3665CH_4 + 13.34CO_2 + 1.45C_5H_7NO_2 \tag{5}$$

$$C_6H_{10}O_5 + 0.351H_2O + 0.2163NH_3 \rightarrow 2.459CH_4 + 2.4592CO_2 + 0.2163C_5H_7NO_2 \tag{6}$$

$$CH_{2.03}O_{0.6}N_{0.3}S_{0.001} + 0.31H_2O \rightarrow 0.401CH_4 + 0.419CO_2 + 0.036C_5H_7NO_2 + 0.001H_2S + 0.264NH_3 \tag{7}$$

Using the information from the model of Taifouris and Martín (2018), together with a series of physical-chemical parameters of the residues (total solids, volatile solids, carbon content, etc.), the model of León and Martín (2016) can adjust the distribution of the different gases (mainly H_2O, NH_3, and CO_2) between the gaseous (biogas) and the liquid phases (digestate). In addition, this new model allows estimating the amount of nutrients (nitrogen, potassium, and phosphorus) that the liquid/solid effluent of the bioreactor has, crucial information to evaluate the usefulness of the digestate produced.

The biogas is purified by using a bed of iron, to remove the H_2S, and a PSA system to reduce their CO_2, NH_3, and H_2O content to achieve an acceptable biomethane composition. The detailed explanation of this process, together with the balances of mass and energy, the thermodynamic models, and empirical yields, is shown in the supplementary material.

2.2.3. Techno-economic analysis and process scale-up

A process is designed for each type of waste, as described in Sections 2.2.1 and 2.2.2, together with the corresponding operational expenditure (OPEX) and capital expenditure (CAPEX), modeling up to 50 designs with different waste treatment capacity. The sizes range from a minimum size, which depends on the minimum amount of waste available considering all the space units of a country; and a maximum size that is fixed by references (Rico, 2020) (for wet residues) or the maximum waste available considering all spacial units (for lignocellulosic waste). Each of these designs is optimized through an optimization model whose objective function is to reduce biomethane production costs.

For the OPEX, both fixed and variable costs are estimated, following the procedure described in Sinnott (2005). The cost of waste is not considered because it is produced at the same place where it is treated and has no market value so far. However, the auxiliary costs (steam, water, and energy) are considered and determined from the mass and energy balances carried out for each of the processes. In addition to these costs, labor, maintenance, laboratories, depreciation, and insurance (all fixed costs) are estimated following the procedure of Sinnott (2005).

Regarding CAPEX, the first step is to estimate the cost of the equipment. Each piece of equipment that constitutes the processes of anaerobic digestion and gasification is analyzed, as well as its size and its cost estimation. For the economic estimation of the reactors, the bed of ZnO, as well as the indirect gasifier, the procedure described in the work of Sánchez et al. (2019) is used. The compressors, heat exchangers, and the fire heater are designed following the correlations shown in the work of Couper et al. (2005), while the electrostatic precipitator, filters, and cyclones are designed based on the studies of Almena and Martín (2016). The digester is designed following the work of Taifouris and Martín (2018). Once the cost of equipment is estimated, the rest of the capital costs (equipment erection, instruments, process buildings, and structures, among others), necessary for the construction and start-up of the factories, can be calculated following a factorial method, which is shown in Sinnott (2005). For more information on economic estimation, please consult the supplementary material.

2.3. Facility location problem

Following the results from the previous stages, an extended location problem is formulated to select the number, size, type, and location of facilities, between the 50 possible designs. It is a mixed-integer linear programming (MILP) that aims at maximizing the total biomethane production for a specific budget. Binary variables are used for plant selection. First, it is necessary to determine the amount of biomethane (Biomet_p) that can be produced in each spatial unit ‘p’. This depends on the number of each type of factory (each design ‘q’ of each kind of waste ‘w’) installed in each spacial unit ‘p’ ($\mathrm{Nfact}_{w,q,p}$) and its biomethane production ($\mathrm{CH_4fact}_{q,w}$), by using Eq.(8).

$$Biomet_p = \sum_w \sum_q Nfact_{w,q,p} \cdot CH4fact_{q,w} \quad \forall p \tag{8}$$

$\mathrm{CH4fact}_{q,w}$ is obtained as a result of the previous stages.

Since the plants installed in a spatial unit ‘p’ cannot consume more waste than is available at that location, it is necessary to estimate the total waste treated by all of the installed plants in a spatial unit ‘p’ ($\mathrm{Wst}_{w,p}$) through Eq.(9).

$$Wst_{w,p} = \sum_q Nfact_{w,q,p} \cdot Wastefact_{q,w} \quad \forall w \tag{9}$$

Where $\mathrm{Wastefact}_{q,w}$ is the treatment capacity of a plant with the design ‘q’ treating the waste ‘w’.

Regarding OPEX and CAPEX of all waste treatment plants installed in a spacial unit ‘p’ (CstO_p and CstF_p, respectively), they are estimated by Eqs.(10)-(11), respectively.

$$CstO_p = \sum_w \sum_q Nfact_{w,q,p} \cdot COfact_{q,w} \quad \forall p \tag{10}$$

$$CstF_p = \sum_w \sum_q Nfact_{w,q,p} \cdot CFfact_{q,w} \ \ \forall p \tag{11}$$

Where OPEX and CAPEX of each of the different designs ‘q’ for each of the different wastes ‘w’ (COfact$_{q,w}$ and CFfact$_{q,w}$) are obtained by following the procedure described in Section 2.2.3. Thus, the total OPEX (Topex) and the total CAPEX (Tcapex) are calculated by Eqs.(12)-(13). Transportation costs are not considered since it is expected that the facilities are located near the areas with a high waste production, due to the high economic and environmental costs associated with waste transportation (Makara and Kowalski, 2018). Therefore, this cost will be negligible compared to the COPEX and OPEX of the factories.

$$Topex = \sum_p \cos tO_p \tag{12}$$

$$Tcapex = \sum_p \cos tF_p \tag{13}$$

Topex must be less than the selected annual budget (Eq.(14)).

$$Topex \leq Annual \ \ Budget \tag{14}$$

With the selected budget, the fraction of natural gas demanded that can be covered by biomethane (fcov$_p$), in each spacial unit ‘p’, is given by Eq.(15), while the total fraction covered (Tfra) is estimated by Eq.(16).

$$f_{\mathrm{cov}_p} = \frac{Biomet_p}{NGas_p} \quad \forall p \tag{15}$$

$$Tfra = \frac{\sum\limits_{p} Biomet_p}{\sum\limits_{p} Ngas_p} \tag{16}$$

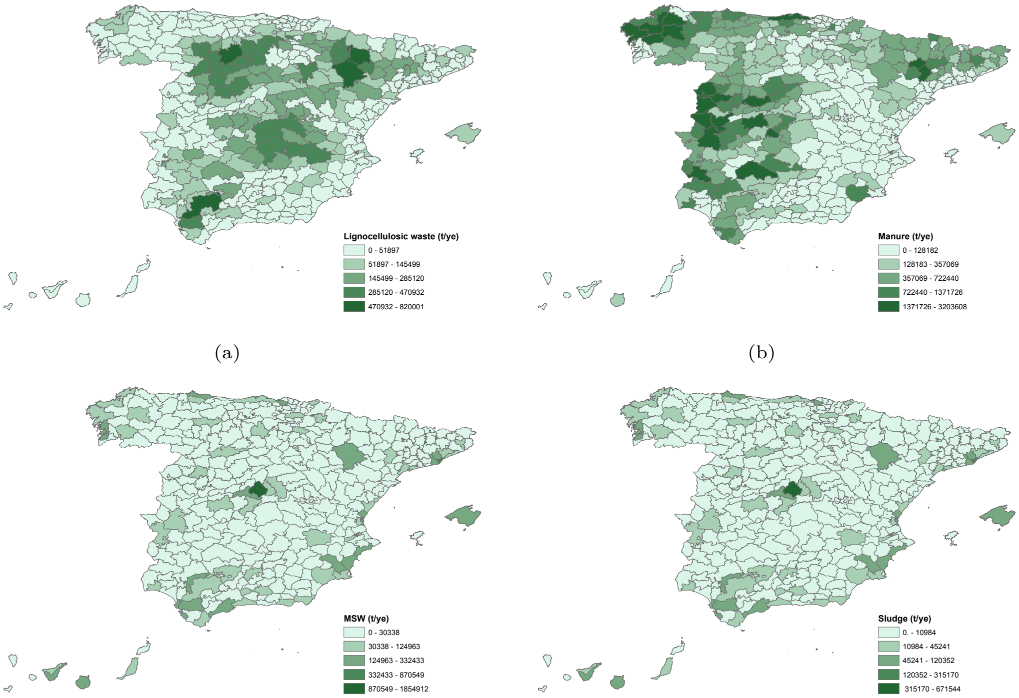
3. Results

3.1. Case of study

The optimization framework presented in previous sections is applied to analyze the reduction of fossil natural gas dependence in Spain toward the circular economy of its waste. The country is divided into agricultural districts, that is, 345 possible locations. Among the different countries of the European Union, Spain has been selected for three reasons. It has a large agro-industrial production (Gobierno de España, 2022), and therefore, a large production of waste. In addition, Spain is highly dependent on foreign natural gas suppliers (Enagas, 2022). Finally, the current production of biomethane is quite limited compared to other countries (European Biogas Association, 2021).

Regarding waste production, Figure 3 shows the spatial distribution of lignocellulosic waste (a), manure (n), MSW(c), and sludge(d), in Spain. Lignocellulosic residues are estimated from annual crop data (Escudero et al., 2021). Manure is estimated from animal census and age distribution (Instituto nacional de estadistica, 2021), while that MSW is calculated from the population of all cities with more than 50,000 inhabitants. In those agricultural districts that have more than one city with these characteristics, their MSW production is added, while in those that only have cities with less than 50,000 inhabitants, their MSW production is assumed to be 0.

The consumption of natural gas can be seen in Figure 4. This consumption can be estimated from reports (Comisión Nacional de los Mercados y la Competenicia, 2021). The technical specifications of the biomethane obtained must comply with the specifications indicated in the reference (Ministerio para la Transción Ecológica, 2018).



(a) (b)

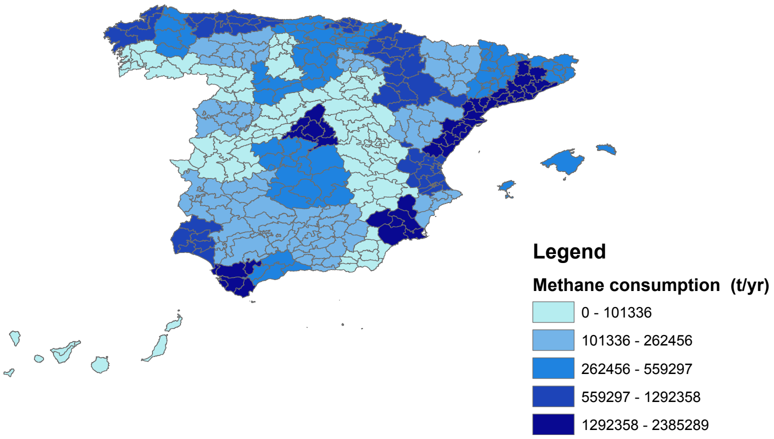
(c) (d)

Figure 3: Amount of (a) lignocelulosic wastes, (b) manure, (c) MSW and (d) sludge

Finally, the optimization framework used for this study consists of two different type of mathematical optimization model. A NLP for each process design, and a MILP for facility location problem, which are solved in an Intel Core i7-7700 computer at 3.6 GHz (4.2GHz as turbo frequency), 65W of TDP, 4 core with 8 threads, and 32 Gb of RAM (1200MHz) by using GAMS.

3.2. Properties of the different types of factories

As explained in Section 2.2.3, 50 different factories, with different production capacities, are designed and optimized for the treatment of the wastes considered, based on the characteristics of the regions considered in this case of study. These spatial units determine the maximum and minimum size of these factories. Once designed, following the procedure described in Section 2, the



(a)

Figure 4: Consumption of natural gas in each agricultural district

waste processing capacity, methane production, as well as OPEX, and CAPEX to build them can be determined. The most relevant data are shown in Table 4. Although the relationship between biomethane production and treatment capacity of the plant is linear with the treatment capacity, the production cost of biomethane follows a power law. This is due to the strong economy of scale since a large part corresponds to fixed costs, above 90%.

Table 4: Main results of the techno-economic analysis of the residues (q: capacity of factory(t/y), WW: wet waste).

Residue	Yield ($kg_{biomethane}/kg_{WW}$)	Production Cost (€/kg_{WW})	Minimum Capacity(t/y)	Maximun Capacity(t/y)
SLUDGE	0.003	$Pcost= 1814278231 \cdot q^{-0.97}$	700624	49754
MANURE	0.012	$Pcost = 160365047 \cdot q^{-0.885}$	63072	367920
MSW	0.070	$Pcost = 72035915 \cdot q^{-0.97}$	19657	52560
LIGNO	0.285	$Pcost = 606041 \cdot q^{-0.626}$	10000	820000

3.3. Total potential of biomethane production in Spain

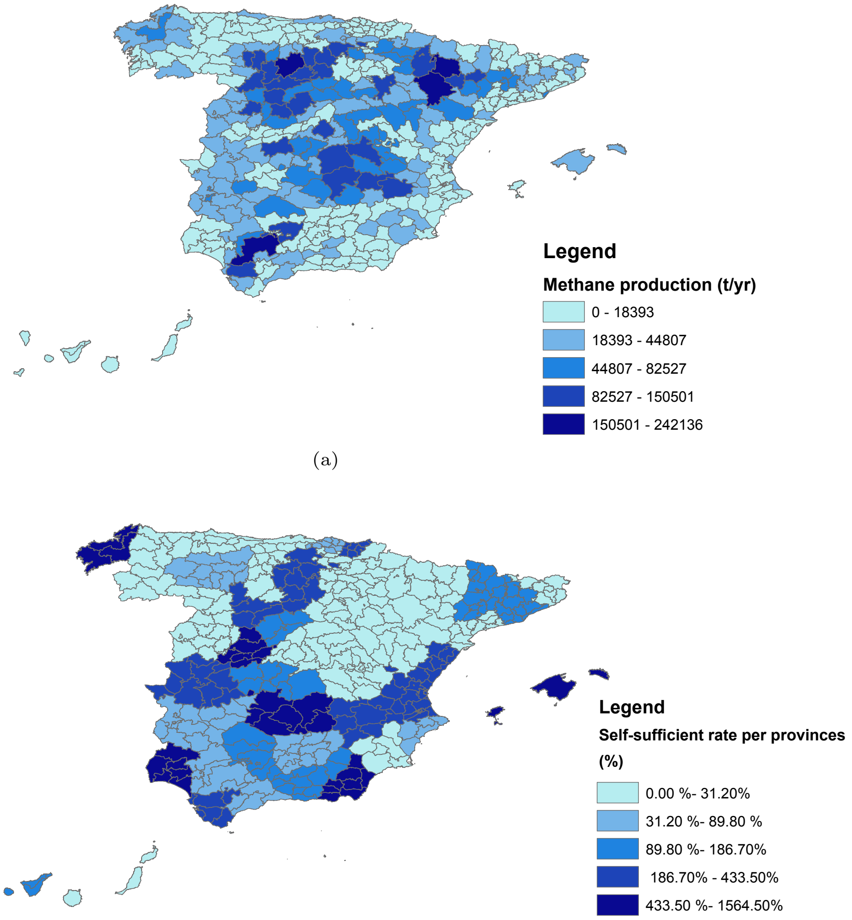
The results show that 43% of natural gas consumed could be supplied through the treatment of the available wastes. However, this requires a total CAPEX of 21391M€, as well as an OPEX of 25852M€ per year. In order to obtain these results, the process design is optimized to maximize biomethane production at each spot, but the localization of the plant is not optimized, as it aims at treating all available waste.

The maximum amount of biomethane that can be produced in each agricultural district is shown in Figure 5a. If this distribution is compared with the amount of residues (Figure 3), it can be observed that the production of biomethane is consistent with the distribution of lignocellulosic waste. This is because most of the biomethane is produced from lignocellulosic waste by using gasification. This technology has a yield of 28.5% (28.5 kilograms of biomethane are generated per 100 kilograms of biomass) while manure, MSW, and sludge have yields of 1%, 7%, and 0.3%, respectively (see Table 4). The large difference between these yields is due to the composition of the waste and the technology used to produce biomethane. Manure, MSW, and sludge use anaerobic digestion, while lignocellulosic waste uses gasification. For this reason, although the amount of residues is larger in the cases of wet waste, the amount of biomethane generated from lignocellulosic wastes is larger (8250 kt/y vs 2103 kt/y).

By analyzing the fraction of natural gas demand satisfied by using biomethane (see Figure 5b), there is a total of 21 provinces that would be totally independent of natural gas with this capital investment. Some of those that have a higher level of independence include 'La Coruña', 'Ávila', 'Ciudad Real', 'Almería' , 'Huelva', and 'Baleares'. In addition, there is an important mismatch between large industrial zones, urban areas, and the main cultivation regions. It is responsible for that difference between production and demand (see Figure 3 and 4). The demand is highly centralized in provinces such as 'Madrid', 'Barcelona', 'Asturias', 'Murcia', and 'Cadiz'.

3.4. Determination of the optimal budget for the reduction of Spain's dependence on fossil natural gas

The facility location problem is used to optimize the selection of the size, type, and location of the facilities for different available budgets. This allows drawing the Pareto curve (Figure 6) between the self-sufficiency ratio and the selected waste treatment budget. The self-sufficiency ratio is defined as the ratio of biomethane produced to methane consumed and is not linear. As can be seen in Figure 6, there are two sections, divided by the point of 5000 M€ per year. In the first section, there is an increase of 2% in the self-sufficiency rate per 100M€ spent, while in the



(a)

(b)

Figure 5: Potential biomethane production (a) per agricultural district and demand for natural gas that it could satisfy per province (b)

second section, the self-sufficiency remains almost constant (0.02% per 100M€ used). Therefore, the point of 5000 M€/year is selected as the best budget to spend on the construction of waste treatment plants in Spain. This OPEX corresponds to a CAPEX of 9505M€.

For this budget, the amount of biomethane generated by the agricultural district can be seen in Figure 7a. This corresponds to 206 lignocellulosic waste , 141 manure, 148 MSW, and 0 sludge

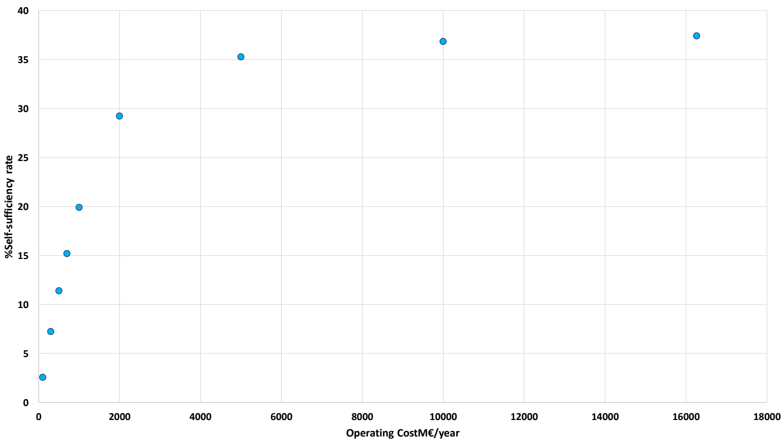
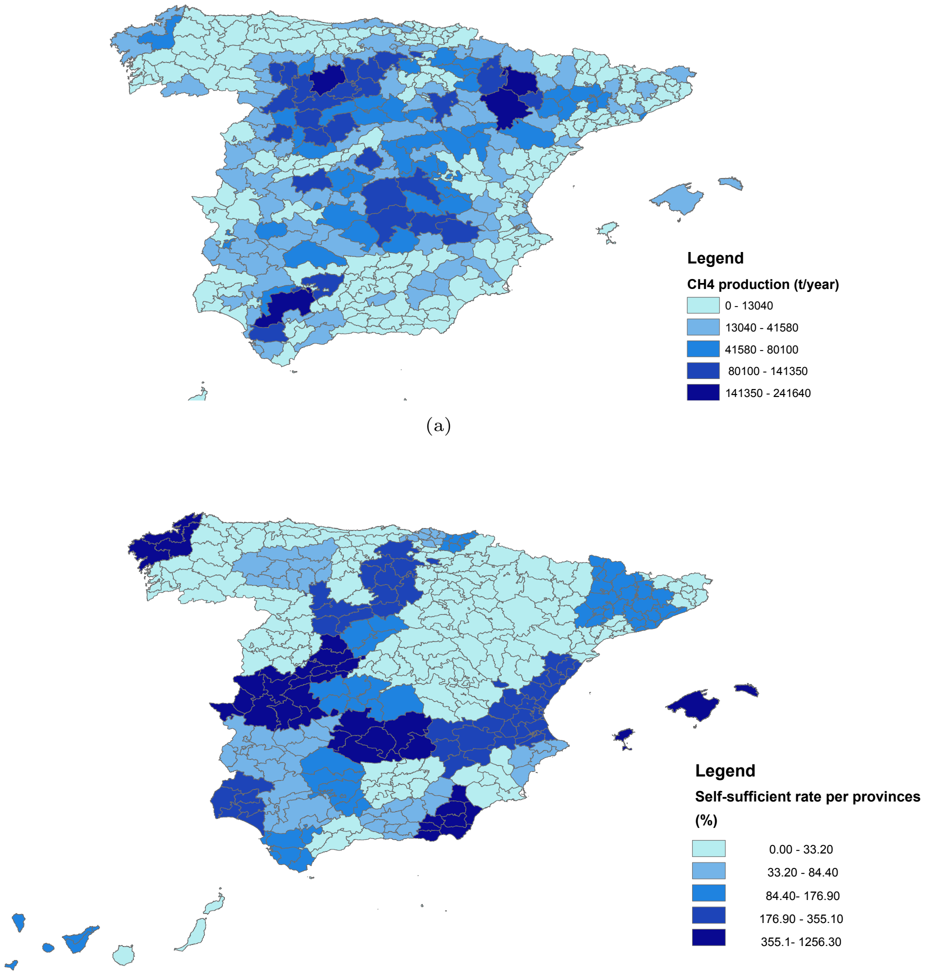


Figure 6: Relation between the budget for operating cost and the self-sufficiency rate

treatment plants , which can be seen in Figures 8 and 9 . With this distribution of treatment plants, it is possible to cover 35% of the country's total natural gas demand, and 19 provinces are totally independent of natural gas from foreign suppliers. These provinces correspond mostly to rural areas, which have a higher concentration of lignocellulosic residues or manure, that is, greater potential for natural gas production and less access to the main gas pipelines.

From techno-economy analysis of the plants, it is observed that 90 % of the operating costs corresponds to fixed costs (labor, maintenance, capital charges, and insurance) while the remaining percentage corresponds to variable costs (raw material, auxiliary services, and energy) in the case of gasification factories.

In anaerobic digestion processes, this distribution is even more uneven, with 99% versus 1%. Since plant size does not have a high effect on operational costs, the economy of scale is even more favored, pushing the selection of plant size to the maximum allowed in each of the selected agricultural districts. In the case of wet waste treatment (MSW and manure), larger designs are selected (above 35,000 tons per year for manure and 50,000 tons per year for MSW), representing 97% of the designed plants. In the case of dry waste, the plants are much larger and in most of the selected agricultural districts, there is not so much waste available for factories of those sizes. Therefore, the most selected plants are small (below 50,000 tons/year), representing 50% of the

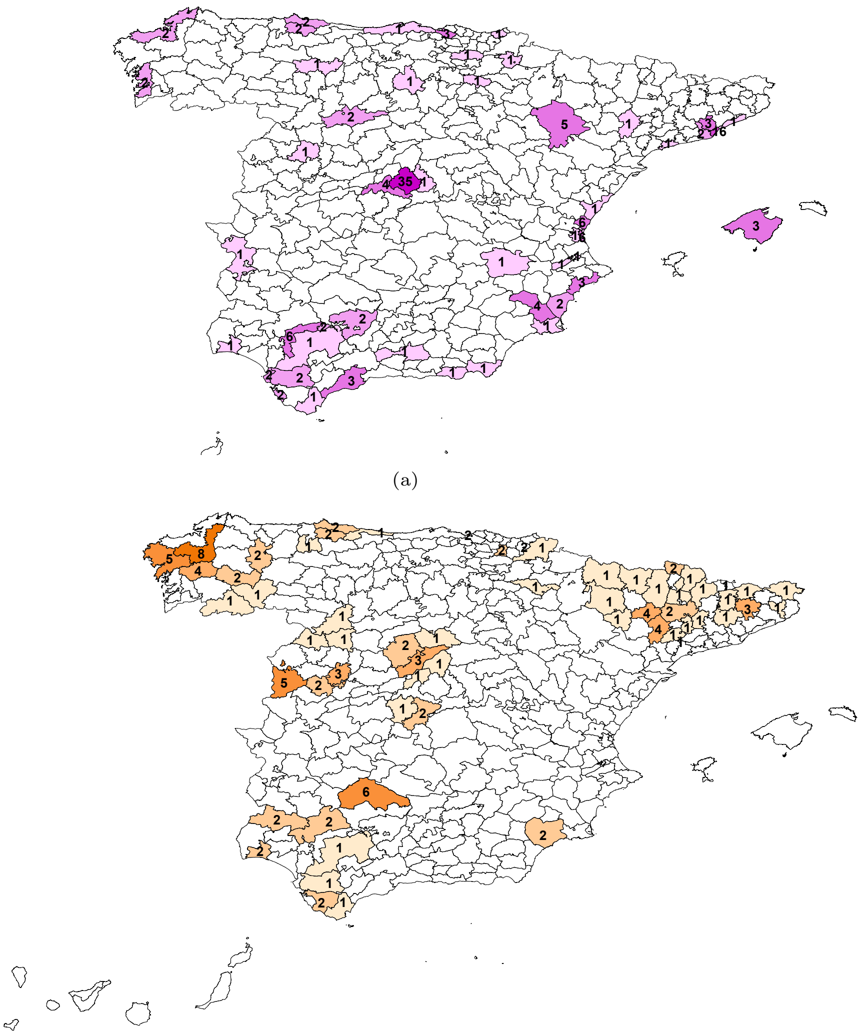


(a)

(b)

Figure 7: Production of Biomethane (ton/year) with a budget of 5000 MM€/year (a) and self-sufficient rate of each provinces (b)

selected plants. 5000 M€ represents 40.6% of the budget of the Ministry for Ecological Transition and the Demographic Challenge (MITECO) in 2021 (Ministerio para la transición ecológica y el reto demográfico, 2020). Considering the OPEX and the total amount of biomethane produced, the unit cost of biomethane is 34.8 €/MWh or 10.19 USD/MMBTU. Since this study is addressing



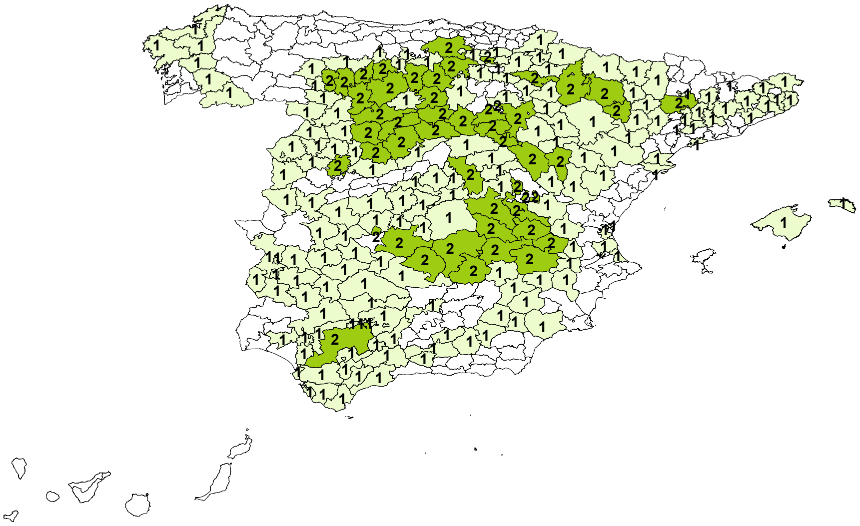
(a)

(b)

Figure 8: Factories for the treatment of manure(c) and msw(d)

a feasibility analysis, the margin of error of the biomethane cost estimate is 30% (Sinnott, 2005). Therefore, this cost is between 7.13 and 13.25 USD/MMBTU and is below the current price of natural gas in Europe (39.02 USD/MMBTU) (World Bank, 2022)

Finally, it is important to highlight that, as in the results shown in Section 3.3, there is a



(a)

Figure 9: Factories for the treatment of lignocelulosic wastes

significant mismatch between the regions that demand natural gas and the districts that generate biomethane (see Figure 7b).

4. Conclusions

Due to the energy dependence of European countries on foreign natural gas suppliers, any disruption in delivery could affect the energy security of a large number of countries. Because of this, together with the environmental problems associated with the generation of waste, it is essential to make the best use of the waste generated by both industry and the population. This work presents a multiscale and holistic analysis to assist in the decison-making process regarding waste treatment. It integrates a series of mathematical models that allow estimating the amount of biomethane that a country can produce, what is the best process and waste for it, the cost and location of the plants, taking into account the number of animals, the annual crop production, and the population of large cities, as well as the available budget.

As regards its application to the specific case of Spain, it was determined that almost half of the natural gas consumed could be produced by treating the total waste available.

By comparing the maximum biogas production potential with the optimal valorization of the available wastes, the results show that it is possible to reduce the total CAPEX and OPEX of the waste treatment plants down by 57.92% and 80.65% respectively, while the percentage of natural gas covered by biomethane was reduced by only 19% percent. Therefore, it is concluded that the point of greatest profitability is reached at 5000 M€ per year of operational costs.

This OPEX is of the order of the budget that is being allocated annually for MITECO. The government invests this budget in the elaboration of various plans for the improvement of water quality, waste treatment and sustainable energy production (Ministerio para la transición ecológica y reto demográfico, 2022b). Among these plans, it has recently developed a specific plan to increase the country's energy security, for which this type of analysis is paramount (Ministerio para la transición ecológica y reto demográfico, 2022a). With this OPEX, 19 provinces can be independent of natural gas from foreign suppliers. Since the gas supply is assured between these provinces, the development of decentralized structures can be taken into account, reducing the stress on the central pipelines. Moreover, by producing the natural gas at the site of consumption, the environmental and economic impacts are reduced by avoiding the necessary transportation between the points of consumption and the nearest pipeline. Therefore, this can be a strong incentive to create energy policies focused on prioritizing the construction of waste treatment plants oriented to biomethane production in these specific areas. From the results of the analysis, it is also concluded that the most cost-effective process is gasification, so the treatment of lignocellulosic waste is prioritized over other wet wastes. This means that most of the plants are located close to the large cultivation areas, that is, around the center of the country.

This analysis is easily applicable to other countries, simply by changing the databases. In addition, certain physicochemical parameters, such as waste composition, can be adjusted for particular cases, in order to improve the estimates, without affecting the procedure described in this work.

Finally, as society moves towards a zero-carbon energy production system, these plants can be easily adapted to produce green hydrogen (Antonini et al., 2020), which can be use either as a fuel or raw material to produces other chemical products.

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