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Techno-Economical Assessment for Combined Production of Hydrogen, Heat, and Power from Residual Lignocellulosic Agricultural Biomass in Huesca Province (Spain)

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Abstract: Nowadays, great emphasis is rightly given in the scientific community to hydrogen production from electrolysis. However, to achieve the politically stated target ambitions, all low-carbon sources for hydrogen production must be considered. The present work proposes a local production system of negative carbon hydrogen from lignocellulosic residual biomass using gasification and gas separation through H_2-selective membranes as enabling technologies. The feedstock is pruning. In addition, the system produces heat and power for a Renewable Energy Community (REC) to increase the economic feasibility of hydrogen production via their sale. A modular basic plant is sized, based on a simplified system envisaged for RECs under the current regulatory framework in Spain (electrical renewable output of 100 kW). A network of these modular basic plants in the province of Huesca (Aragón) is simulated to create a system of hydrogen refueling stations for mobility in that area. A Levelized Cost of Hydrogen (LCOH) is proposed, comprehending the whole production chain from "field to tank", which is significant in areas where there is no infrastructure for the production and distribution of hydrogen for automotive purposes. The resulting LCOH for the whole system is 8.90 EUR/kg. Sensitivity analysis potentially values a lower LCOH, which unveils that hydrogen mobility can be largely competitive with diesel one.

Keywords: Renewable Energy Community (REC); hydrogen; Levelized Cost of Hydrogen (LCOH); lignocellulosic biomass; shared energy; distributed energy system; combined heat and power (CHP); hydrogen refueling station (HRS); membrane separation; carbon negative

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1. Introduction

To reach the goal of a net zero carbon society in Europe, low-carbon hydrogen has a key role. The production of hydrogen via electrolysis seems to be one of the most prominent generation pathways: up to 1300 GW of electrolyser could be installed by 2050 in Europe [1].

The EU claims the principle of technology neutrality to reach its objective regarding low-carbon hydrogen generation: Deutscher Verein des Gas und Wasserfaches and Hydrogen Europe [2] stated that if Europe wants to be climate neutral in few years, all options have to be used, and they described opportunities for the pyrolysis of natural gas and biogas to produce hydrogen with low or even negative carbon emission if it is captured in a solid form. Vogel and Hickel [3] stated that high-income countries are far from their Paris target and an enhancement in the decarbonization rate by a factor of ten by 2025 is required to comply with +1.5 °C global warming. Hydrogen production from biomass is an alternative pathway that could be considered, in particular, for small plants that could use residual biomass from the agricultural sector. In all European countries, lignocellulosic agricultural biomass is considered a waste material, which is marginally used for energetic purpose via traditional and low-efficiency techniques [4].

Lignocellulosic agricultural biomass represents a completely different sector in comparison with intensive forestry cultivation in North-Central Europe: it has a marginal role in agricultural European economy due to low energy content, low density over the land, low potential added value [5]. A complete overview of different pathways to valorize lignocellulosic agricultural biomass was recently presented by Blasi et al. [6] showing potential production of biofuels, biochemicals, and biocomposites.

Lignocellulosic agricultural biomass appears well usable for a small-scale economy. The definition of Renewable Energy Community (REC) in the European Directive on Renewable Energy (so called RED II) [7] could be a new opportunity for energetic valorization and exploitation of residual lignocellulosic waste materials from the agricultural sector, such as pruning. The main purpose of a REC is "to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits", as stated in Article 2 number (16) of RED II [7]. A REC can produce, consume, store, and sell renewable energy in different forms: for example, heat, power, and hydrogen.

Wang et al. [8] described an optimized system to produce different energy vectors to better deploy renewables' advantages at a regional territorial level. Mustafa et al. [9] stated that it is feasible in a local community in Norway to produce biofuel for local mobility from the gasification of local biomass from forests. The potential biofuel production from lignocellulosic local waste was huge (about three times) with respect to the demand for public transport requirements. The payback period for the proposed plant was only 4 years. There was no mention of combining the production of heat and power.

Situmorang et al. [4] described the worldwide diffusion of small biomass gasification systems, in particular, for rural and local communities and their limit for implementation. Hydrogen direct production was mentioned as one of the alternatives, such as coupling with an Internal Combustion Engine (ICE).

Diaz et al. [10] overviewed the coupling of biomass as an energy source for use in ICEs through a gasification process, emphasizing its advantages (mainly high flexibility in the use of different types of biomass and the high reliability of ICE technology) and highlighting its limitations (mainly the criticality of designing the biomass supply chain in order to limit its supply costs and the lack of knowledge about biomass gasification at the local community level). No combined production of hydrogen, heat, and power is mentioned.

Tomin et al. [11] described a Renewable Energy Community in Japan based also on biomass local sources. The use of biomass, integrated with wind and solar, has enabled a high penetration of renewables in the energy community.

To the best knowledge of the authors, no paper describes a system based on residual lignocellulosic biomass to produce both hydrogen for mobility and heat and power for the residential sector. The main enabling technologies for the proposed system are biomass gasification, hydrogen membrane separation, and the production of heat and power using an ICE fed by a low-heating-value syngas.

The main purpose of the present work is to describe, to size, and to economically assess a set of co-ordinated energy plants producing combined hydrogen for mobility and heat and power for residential use (Figure 1). Each plant integrates a REC as defined in the European regulatory framework, placed in the province of Huesca in Aragón (Spain). Each plant uses local pruning from the agricultural sector as feedstock. Hydrogen refueling stations (HRSs) enabling local mobility are included in the evaluations. To the best knowledge of the authors, this purpose represents a novel approach in the literature.

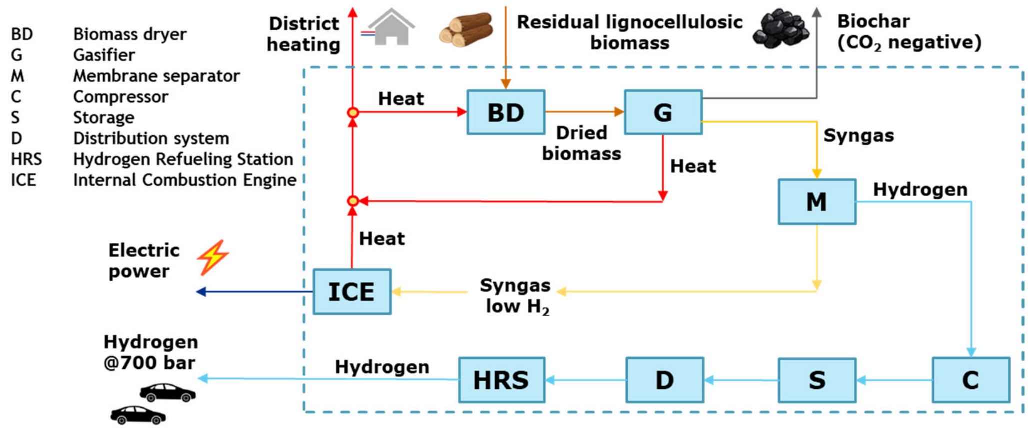

Figure 1. Simplified scheme of the proposed energy plant.

2. Materials and Methods

The presented study includes a technical–economic assessment of a system composed using different technologies linked together in an innovative way. All the technologies contribute to the creation of a local hydrogen production chain for mobility purposes, in an area that is completely lacking in it, despite having the potential for it. The province of Huesca in Aragón (Spain) is chosen as the analysis area: it is a logistical hub between Zaragoza, the Pyrenees, and Barcelona; it is an agricultural area with ample availability of biomass. All technologies in the study are at the commercial stage or they will be within a few years.

This section will provide references to the scientific literature, corporate marketing documents, and European and Spanish legislation that served as the premise for this study. In detail, the following will be addressed:

- Renewable Energy Communities in the Spanish electric market;
- Biomass resources in Aragón;
- Harvesting and gasification of the residual lignocellulosic biomass;
- Hydrogen separation in selective membranes and syngas treatment;
- ICE fed by low-heating-value gases;
- District heating in Spain;
- Hydrogen refueling stations and car fleet characterization;
- REC modeling;
- Economic analysis.

2.1. *Renewable Energy Communities in the Spanish Electric Market*

The European Directive on Renewable Energy (RED II) [7] described RECs as new legal entities for small-scale decarbonization, designed for both residential end-users and small and medium enterprises (SMEs) [12–15]. Real Decreto (Royal Decree RD) 23/2020 on 23 June 2020 [16] under Art. 4 introduced the term "renewable energy communities" into the Spanish legislation. As in many countries in Europe, the REC concept is not easy to integrate into the pre-existing regulatory framework of decentralized and renewable power production [17].

Previously, as stated by Gallego-Castillo et al. [18], Real Decreto 244/2019 on 5 April 2019 [19] introduced two classes of power (up to 100 kW and over 100 kW) for renewable plants, introducing a simplified regime for the first one and equating a class greater than 100 kW to renewable plants that sell energy to the wholesale domestic market. For renewable plants up to 100 kW, a simplified billing system is allowed, consisting of a direct discount on the customer electric bill for energy sold to the grid, with the limitation that the total economic value of the sold energy (energy exported out of the REC) cannot exceed the economic value of the purchased energy (energy imported into the REC). Any excess in the value of sold energy (compared to the purchased one) is, in fact, not paid to the producer.

As Caballero et al. [20] stated, RECs can use this form of incentive in Spain, because no direct payment of incentives is expected, together with the lower payment in the bill for self-produced energy in a shared plant (self-sufficiency of the REC). Self-sufficiency indicates the percentage of community consumption that has been satisfied by the generation in the community itself.

RD 244 introduced and allowed a common shared renewable plant for a REC, but the REC's members as consumers have to be at a maximum distance of 500 m from the generation plant. This constraint is a strong limitation for the development of the initiatives. As pointed out by Caballero et al. [20], the ulterior Real Decreto 29/2021 on 21 December 2021 [21] established that the electric connection of the renewable plant can be at both low and medium voltage levels.

Caballero et al. [20] stated that RECs in Spain can use multiple renewable sources and no limitations regarding the type of renewables are imposed, as is the case, for example, in Italy (Art. 2 comma 1 lett. a in [22]). Moreover, it is underlined that the aim of the REC in Spain is to increase the levels of self-consumption and self-sufficiency by adopting different energy carriers (e.g., hydrogen, heat, and power).

Gallego-Castillo et al. [18] inferred that self-consumption installations shared by several consumers are allowed in a Spanish REC and also that nearby consumers can share energy from the same sole power plant. The final user and owner of a generation plant have to be different entities: consequently, a company, such as a cooperative, that will be the owner of the renewable power plant is necessary to constitute. In their work, the authors described the different components for electric price definition in Spain and explained the difference between the economic value of imported (purchased by a REC v_{pur}) and exported electricity (sold by a REC v_{sol}). They are based on the Voluntary Price for Small Consumers (*PVPC* as for the Spanish acronym) and energy component of the access tariff (*TEU* as for the Spanish acronym):

$$\begin{cases} v_{pur} = PVPC + TEU \\ v_{sol} = v_{pur} / R_{imp/exp} \end{cases} \tag{1}$$

where $R_{imp/exp}$ is the ratio between v_{pur} and v_{sol}, and it is assumed to be equal to 1.39; the *TEU* is considered constant over the last few years at a value equal to 44 EUR/MWh [18].

The *PVPC* is considered as the medium value in the period between January 2023 and April 2023 and is equal to 153.97 EUR/MWh [23]. Using the mentioned values, the values of electricity purchased and sold by the REC can be considered:

$$\begin{cases} v_{pur} = 109.97 \text{ EUR/MWh} \\ v_{sol} = 79.32 \text{ EUR/MWh} \end{cases}. \tag{2}$$

2.2. Biomass Resources in Aragón

Considering only the first three most abundant cultivars in Aragón (almond tree, vineyard, and olive tree), which cover around 80% of cultivated area [24], the total annual lignocellulosic biomass available in the region from annual pruning is around 269,000 ton/year, with a moisture content around 15%, produced on around 243,500 ha [25–27] in the region.

2.3. Harvesting and Gasification of the Residual Lignocellulosic Biomass

Different mechanized systems for pruning harvesting have been defined over the last few years [28,29], such as for pruning transportation [30–32]. These technologies can be considered to be at commercial stage. From a literature review, the total cost of the lignocellulosic biomass to be used for gasification purpose is defined, and it is described in Table 1.

Table 1. Lignocellulosic biomass harvesting and transformation costs.

Working Phase	Cost	Ref.
Harvesting biomass dumped at roadside	40.0 EUR/ton	[29,33]
Transportation (50 km distance)	10.4 EUR/ton	[32]
Briquetting (without drying OPEX)	33.7 EUR/ton	[34]
Total cost	84.1 EUR/ton	

Using the residual heat produced by the proposed system, during periods when there is no heat request from REC members (district heating), the biomass is dried and processed into briquettes for subsequent gasification [34,35].

Briquettes of this kind of biomass can usefully feed a commercial air downdraft gasifier such as the one provided by RESET S.p.A. (Rieti, Italy), an Italian company manufacturing small CHP plants [36] with up to 200 kW of electric power output. According to the company data, using common agricultural lignocellulosic waste materials such as pruning, the dry syngas composition contains an average of around 16% vol. of hydrogen with no tar (detailed composition in Table 2).

Table 2. Dried volume syngas composition from gasifier.

CO	H_2	CH_4	CO_2	N_2
20%	16%	2%	10%	52%

The temperature of the syngas at the outlet of the gasifier is 600 °C, as declared by RESET, and its lower heating value is assumed to be 4.957 MJ/Nm^3 (4.405 MJ/kg). The data are well aligned with the literature and indicate that the technology used by RESET is widespread and consolidated [37–39].

2.4. Hydrogen Separation in Selective Membranes and Syngas Treatment

Hydrogen can be extracted from a stream of syngas, partially or totally, using palladium-based membranes and also from a small-scale hydrogen production with high purity [40–42]. The TRL of this technology has increased over recent years and some companies are arising in the market to offer the design of membrane reactors and the supply of systems [43,44].

The membrane technology works with a syngas at around 350–500 °C and at pressure between 3 and 25 bar with no poisoning elements from the membrane surface (like sulphur compounds) in the stream. Over the last few years, dense metallic membranes have been widely studied by Tecnalia research center and Eindhoven University of Technology [45] as a promising solution for hydrogen separation.

Cylindrical membranes have been realized, by depositing a thin (1–10 μm) Pd/Ag layer though an electroless plating technique on a ceramic porous support, with an external diameter of 14 mm and an internal diameter of 7 mm [46]. Recently, an additional ceramic porous protective layer has been developed, leading to the so-called double-skin membranes, in order to improve their resistance to attrition in fluidized bed reactors and improve perm-selectivity, since the protective layer can close some defects of the membrane [47]. These membranes are able to reach a perm-selectivity of about 30,000 at 500 °C; during long-term operations they showed a decrease in perm-selectivity of about 0.33 per hour under fluidization exposure, consistent with what was previously obtained by Nooijer et al. [48], where the decrease was 0.2 per hour in an empty tube (without fluidization exposure). A perm-selectivity of 30,000 means a hydrogen purity of 99.997%. Assuming a decrease of 0.33 per hour, a purity of 99.97% can be reached after approximately 9 years, or after 15 years using the value measured in the empty tube. This latter value of purity is considered the limit of membrane operation, since this is the value required for hydrogen purity for a fuel cell vehicle in the standard ISO 14687:2019 [49,50].

Hydrogen permeation through Pd-based membranes can be described by the solution–diffusion mechanism: hydrogen molecules in the gas are adsorbed on the membrane surface and split into hydrogen atoms, which dissolve in the metallic layer [51]. Due to the presence of a driving force, related to the different hydrogen partial pressures at the two sides of the membrane, hydrogen atoms diffuse throughout the membrane; they recombine in a H_2 molecule and are then desorbed, ending up in the permeate stream. This mechanism is mathematically described by the solution–diffusion model, which is widely used to describe hydrogen permeation through Pd-based membranes [52]. The total flow rate of hydrogen separation, in a 1D representation, can be calculated as follows:

$$\dot{n}_{H_2\,sep} = \int \pi \cdot d_{ext} \cdot (1 - CPC) \cdot Per^0 \cdot \exp\left(-\frac{E_a}{R \cdot T}\right) \cdot \left[(p \cdot x_{H_2})^n - p_{perm}^n\right] \cdot dz \quad (3)$$

where z is the axial co-ordinate, d_{ext} is the external diameter of the membrane (14 mm), Per^0 is the pre-exponential permeance, E_a is the activation energy, T is the temperature, p the retentate-side pressure, p_{perm} the permeate-side pressure, and x_{H_2} is the hydrogen molar fraction in the retentate stream. The syngas after the extraction of hydrogen is named retentate. The pressure exponent n is a parameter which depends on the rate-limiting step in the solution–diffusion mechanism, and is generally bound between 0.5 and 1. In Equation (3), all parameters can be considered constant along the membrane, except for the hydrogen molar fraction x_{H_2}, which depends on how much hydrogen is permeated in each axial position.

The coefficient (1-CPC) is introduced to account for concentration polarization (CP) losses, since the hydrogen fractions involved are quite low (14% molar at the inlet), and uses the concentration polarization coefficient (CPC), which is a parameter bound between 0 (if no CP in present) and 1 (in case of infinite CP). Values for the membrane parameters and for the CPC are reported in Table 3.

Table 3. Membrane parameters.

Parameter	Value	Ref.
Per^0 $[\frac{mol}{m^2 \cdot s \cdot bar^{0.749}}]$	1.3054	[41]
E_a [J/mol]	7810	[41]
n [−]	0.749	[41]
CPC [−]	0.8	[52]

A gas conditioning system has to be designed to create the optimal working conditions for the membrane in terms of temperature and pressure: heat exchangers and a compressor for syngas are required for this purpose.

An Atlas Copco (Nacka, Sweden) HX&HN-15 oil-free intercooled reciprocating compressor [53] (a commercial model) is taken into account for the plant, operating within the range of flow rates and pressures required by the application under study.

In order to achieve an energy-efficient gas treatment system, a turbine expands the compressed and hot retentate coming out of the membranes. The turbine is coupled to an alternator to produce electricity, which is used for the internal needs of the energy system proposed, thereby lowering its own electric consumption. The expansion of a fuel gas at high pressure is well discussed in the literature with potential commercial applications: i.e., harvesting of energy from a high-pressure methane pipeline connected to a low-pressure methane distribution grid [54–56]. The D6100E class turbine from Deprag (German company, Amberg, Germany) is chosen for the study [57]. The turbine for the retentate is modeled based on the information available from the Deprag websites [54,57] and based on Weiss et al. [55]. In particular, the isentropic efficiency is set equal to 0.69, obtained using an inlet pressure close to 14 bar. Electrical–mechanical efficiency of the turbine is set at 85% [39].

The pressure drops implemented before the compressor (4%) and before the turbine (2%) are chosen in accordance with Rovense et al. [58].

The heat exchanger thermal efficiency is set at 90% and the minimum temperature available for heat harvesting to be used in district heating is set at 90 °C; the heat of the syngas or fluids (in ICE) at a lower temperature is dispersed into the atmosphere.

2.5. ICE Fed by Low Heating Value Gases

It is important to highlight that the removal of hydrogen from the syngas stream inevitably reduces the heating value of the gas mixture. This lower heating value may lead to misfiring and poor functioning of the ICE system.

Therefore, to properly realize a combined heat and power (CHP) plant, the minimum lower heating value (LHV) for the gas feeding the ICE is set to 3.8 MJ/Nm^3 [59,60], and the power derating cannot overcome 70% of the power output when fed with methane [61]. The characteristics for the power train in the CHP are from the MAN E3262 E302-V12 engine (MAN, Munich, Germany) originally fed with methane. The engine is used by RESET in its biggest solution. The engine efficiency using methane is 39.6% [62] and the electrical efficiency of the connected alternator is supposedly 95% [61].

2.6. District Heating in Spain

In Spain, the annual thermal demand in the residential sector is usually around 3350 h in a year [63]; in a year, with a continuous production of heat (i.e., from an ICE), only around a third of heat can be valorized in district heating to space heating and domestic hot water. District heating efficiency is assumed to be 93% [64] and annual Spanish energy consumption for space heating and domestic hot water is 177 kWh/m^2 (considering buildings built by 2011) [65].

The cost of energy in district heating in Spain is inferred starting from the analysis of Soltero et al. [63] in the Spanish market in 2014, Comodi et al. [66] in the Italian market in 2016, and considering the cost of energy in Milan's (Italy) heat district in 2023 [67]; the same trend in cost is supposed in Spain and Italy. The obtained cost of energy in district heating is 90.59 EUR/MWh. This value is aligned with data from the Spanish gas market in the first half of 2023 [68].

2.7. Hydrogen Refueling Stations and Car Fleet Characterization

Caponi et al. [69] reviewed several hydrogen refueling station (HRS) installations, summarizing cost and economic performances. The average ratio of CAPEX to hydrogen dispensed daily for a HRS can be set at 5300 EUR/(kg/day). Moreover, Mayyas et al. [70] detailed the cost of each single element in the HRS (compressor, storage, dispenser, pre-cooler, installation cost, and general cost).

Both fuel cell and ICE hydrogen cars are considered in the study, which are passenger cars in both cases. Consumption is set equal to 1.1 kg of hydrogen each 100 km [71,72] for both power trains. The annual mileage of each car is set at 15,000 km/year [73].

2.8. REC Modeling

The characterization and sizing of the REC is based on the previous works of Raimondi and Spazzafumo [74,75]. They allow us to define the residential electricity consumption of a group of people who are part of a renewable energy community, foreseeing their electrical demand each hour in a year.

Although defined for the Italian panorama, the same electrical consumption is assumed for the Spanish scenario, due to having a similar latitude (similar day duration) and due to socio-economic uniformity between the population in Aragón and central Italy.

2.9. Economic Analysis

The general economic parameters used in the study are collected in Table 4. The exchange ratio between the EUR and USD is considered equal to 1.

Table 4. Economic parameters.

Parameter	Value	Ref.
Lifetime, *ny* [year]	20	[74]
Interest rate, *d*	5%	[76]
Biomass power generation capital cost [EUR/kWe]	5200	[77]
Membrane capital cost [EUR/m^2]	5700	[78]
Syngas compressor capital cost [EUR/kW]	690	[40]
Syngas turbine capital cost [EUR/kW]	1000	[55,56]
Hydrogen stationary storage (200 bar) capital cost [EUR/kWh]	13.5	[75]
Hydrogen mobile storage (200 bar) capital cost [EUR/kWh]	17.6	[79]
Hydrogen stationary storage (900 bar) capital cost [EUR/kWh]	24.3	[69]
Hydrogen compressor capital cost [EUR/kW]	6700	[75]
Medium truck for hydrogen transportation capital cost [EUR]	41,100	[80]
Heat exchanger (gas–gas) capital cost [EUR/kW]	187.5	[81]
Heat exchanger (liquid–gas) capital cost [EUR/kW]	210	[82]
Gasifier O&M cost [% of CAPEX]	6.0%	[33]
Heat exchanger O&M cost [% of CAPEX]	3.8%	[82]
Reactor and membrane O&M cost [% of CAPEX]	4.5%	[42]
Hydrogen storage O&M cost [% of CAPEX]	0.5%	[75]
Hydrogen and syngas compressor O&M cost [% of CAPEX]	4.0%	[83]
Syngas turbine O&M cost [% of CAPEX]	4.0%	
Hydrogen refueling station O&M cost [% of CAPEX]	3.0%	[69]
Human labor for H_2 production and logistic [EUR/year] (×2)	72,000	[84]
Truck O&M [EUR/km]	0.28	[85]

The duration of the initiative is set equal to the lifespan of the renewable energy communities, as assumed in Raimondi and Spazzafumo [74].

The capital cost of biomass power generation in the literature has a wide range of variability, depending mainly on the geographical place of installation. It includes the gasifier, syngas purifier (removing ashes) and dryer, and ICE-based electric generator.

Rentizelas et al. [33] declared a cost of 2500 EUR/kWe in Greece for 1 MWe; from the IRENA 2021 outlook [77], an average value of 5200 EUR/kWe is inferred for 0–5 MWe in Europe, in a wide range of cases. The latter value is compliant with information from the RESET website at FAQ section [36].

The capital cost of membrane production is taken from the work of Nordio et al. [78], which reports specific production costs per unit area of permeable surface. The membrane area required for the separation is estimated using a 1D model of the permeation process, as described in Section 3.2.

Weiss et al. [55] and Galanti and Massardo [56] stated the same value for a microturbine capital cost in the power range of tens of kW. In this study, the microturbine is used as a power recovery in syngas treatment.

Hydrogen mobile storage is a cylinder storage on a chassis of a trailer: cost is inferred via a direct interview at Calvera Hydrogen S.A. (Spanish company, Épila, Spain) [79].

Regarding operation and maintenance (O&M), the annual cost for the syngas turbine is assumed to be the same as the syngas compressor, because it belongs to the same technical sector.

Regarding the costs related to the working personnel, two employees who are responsible for maintaining the gasifier and refilling the HRSs are considered with a gross monthly cost of 3000 EUR/month per person [84].

A Levelized Cost of Hydrogen (LCOH) is evaluated for the investigated scenario, taking the Levelized Cost of Energy (LCOE) definition of the Department for Business, Energy & Industrial Strategy as the main reference [86]:

$$LCOH = \sum_{t=1}^{ny} \frac{C_t + O\&M_t - S_t - R_t}{(1+d)^t} / \sum_{t=1}^{ny} \frac{Q_{H_2,t}}{(1+d)^t} \quad (4)$$

considering all capital costs C_t, operation and maintenance costs $O\&M_t$, savings on the electric bills of REC members S_t, and revenues from heat in district heating R_t. The quantity of hydrogen produced $Q_{H_2,t}$ is the same in each year, as well as electricity production and sharing. The investment lifetime in number of years and interest rate are indicated using ny and d, respectively.

Hydrogen as fuel in the transport sector will be a real alternative if the kilometer cost of a hydrogen vehicle is less or equal to the fossil fuel kilometer cost.

In a simplified approach, only the cost of fuel and, in particular, the cost of diesel is considered to define the mileage cost of a car. For a diesel passenger car with a consumption of 20 km/liter and a cost of diesel at the refueling station (VAT included) in Spain of 1.58 EUR/liter [87], a hydrogen car has the same kilometer cost with a hydrogen price of 6.87 EUR/kg (21% VAT included). The hydrogen consumption for a passenger car is considered equal to 1.1 kg/100 km, as declared.

3. Results and Discussion

3.1. Overview of the Proposed System

This study integrates different technologies, with the aim to create a hydrogen, heat, and power combined production chain in the Aragónese province of Huesca in Spain, via a series of interdependent plants.

The modular basic plant is described in Figure 2.

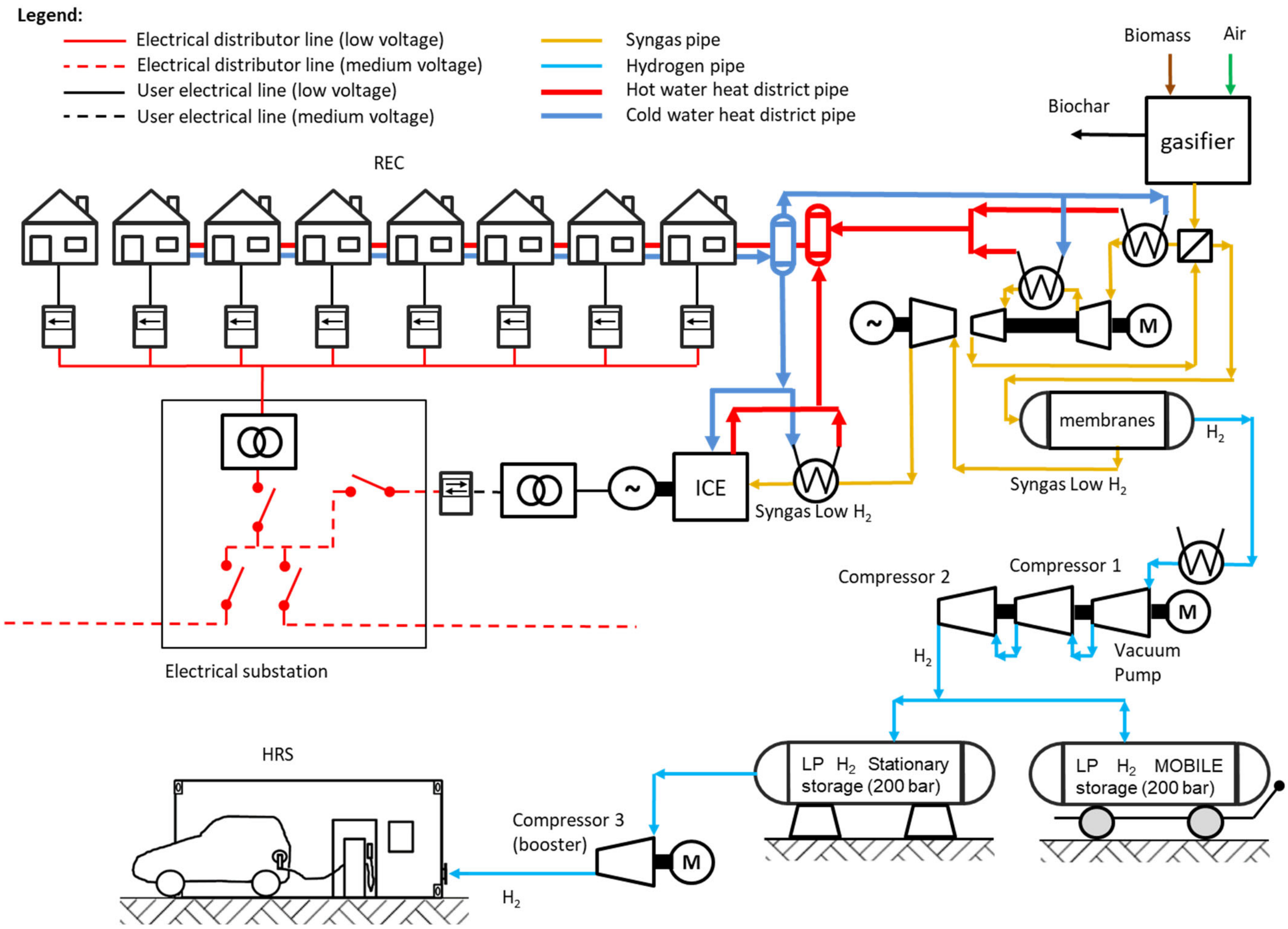

Figure 2. Balance of the modular basic proposed plant.

The feedstock used is lignocellulosic biomass from annual pruning of local crops in Aragón. This biomass is gasified in a series of downdraft commercial reactors, that allow carbon capture by producing biochar. The hydrogen contained in the syngas is extracted using Pd-based membranes and made available to a network of local hydrogen refueling stations.

The low-hydrogen-content residual syngas (retentate) is used in an ICE for the production of electricity which supplies a REC, contributing to the economic sustainability of the initiative, thanks to the Spanish shared energy valorization mechanism.

The waste heat from the process is valorized for heating some members of the REC and, in periods of the year with low residential heat requests, to dry biomass for consequent gasification. A series of HRSs in the province of Huesca, served by a stationary and mobile hydrogen storage system, allows us to create a network in the province and enable hydrogen mobility.

A REC, as a legal entity, manages the whole system, selling electricity exclusively to its members, and heat and hydrogen to its members or, anyhow, to someone in the territory where it is established.

Renewable electric power feeding the REC allows, in the simplified framework for Spanish regulation, a direct discount on the electric bill of REC's members. The monthly savings on electric bills are supposed to fully devolve from members to the REC entity, to sustain hydrogen production for local transportation, using lignocellulosic biomass from local pruning in Aragón farming. As direct consequences of the REC implementation, local jobs will be generated; pruning, which is commonly a waste material, will be greatly valorized; and local pollution will be reduced by promoting the diffusion of zero-emission hydrogen vehicles and sustainable local district heating.

All these activities are in line with the REC general purposes: REC members under these hypotheses do not obtain any economic advantage.

3.2. Characterization of the Subsystems

Starting from the dried volume syngas composition of Table 2, a deeper characterization of the gasifier and ICE is defined. It is considered, in the pruning, to be a content of carbon by weight of 50% and of hydrogen of 6% [88]. The water content in the biomass after drying is set at 12%. Moreover, considering biochar production according to RESET specifications and an electrical efficiency of 95% for the MAN generator [61], the engine efficiency is defined using the composition of syngas from a gasifier. The inferred value is 29.02%. It is aligned with the statement of Gobbato et al. [61] considering the derating of efficiency in comparison with methane of a similar engine fed with syngas similar to this study.

With this assumption, the wet weight composition of syngas is also inferred, as described in Table 5.

Table 5. Wet weight syngas composition from gasifier.

CO	H_2	CH_4	CO_2	N_2	H_2O
18.5%	1.1%	1.1%	14.6%	48.1%	16.6%

This composition is used to define specific heats of syngas to characterize the first heat exchangers and, without water, the compressor behavior (Table 6). In fact, a complete drying of the syngas is foreseen after the first heat exchangers.

Table 6. Specific heats and gas constant (at 700 K).

	c_p [kJ/kg k]	c_v [kJ/kg k]	k	R [J/kg k]
Syngas from gasifier (wet)	1.439	1.072	1.342	
Syngas from gasifier (dry)	1.311	0.965	1.358	329.69
Retentate from membrane (dry)	1.225	0.904	1.356	305.26

Atlas Copco HX&HN-15 is a double intercooled stage piston compressor. It is chosen for its compatibility with the syngas and for its oil-free functioning behavior. Moreover, it operates in the range of pressure and mass flow compliant with the size of the system. The technical datasheet is not sufficiently detailed for the simulation. According with general data from Atlas website [53], isentropic adiabatic efficiency is inferred equal to 85.9% for each of the two stages of the compressor, using a well-known adiabatic isentropic mathematical model for the compressor.

A ratio between the heat power removed in the interstage refrigeration and the electrical power of the motor is also inferred equal to 0.6 to characterize the system energetic simulation. The electro-mechanical efficiency of the compressor is set equal to 85% according to Di Marcoberardino et al. [40].

In the proposed scheme, the syngas is produced using an atmospheric downdraft gasifier, with a temperature at the exit of the gasifier of 600 °C, as declared by RESET. It is cooled down using a regenerative heat exchanger and a water–syngas heat exchanger. This cooling allows us to minimize the energy consumption of the syngas compression phase, required to bring the pressure from a value close to the atmosphere up to the value for hydrogen separation via Pd-based membranes.

The membranes can work at different pressure values [40]. The value is chosen to optimize energy recovery via the downstream retentate expansion in the turbine.

Hydrogen permeation through Pd-based membranes is evaluated using Equation (3), considering a syngas temperature (T) of 500 °C, a retentate-side pressure (p) of 14.58 bar, and a permeate-side pressure (p_{perm}) of 0.2 bar.

Using these values in modelling evaluations, a membrane area of 5.16 m^2 is required to separate 50% of the hydrogen from the syngas: this percentage of removal is well explained and motivated as a consequence of engine constraints in the following Section 3.3. Given the production cost of 5700 EUR/m^2, as reported in Table 4, the cost of the membranes is estimated to be EUR 29,469. Since the amount of hydrogen separated is 89.8 kg/day, the specific cost of the membranes per unit of kg_{H2} per day results in 328 EUR/(kg_{H2}/day).

Hydrogen is extracted using membranes that are connected to a vacuum pump (around 0.1 bar [40]), and with other two stages it is compressed up to 200 bar. For the purpose of this study, it is important to define the total power of the extraction and compression system, based on the hydrogen mass flow rate. Spazzafumo and Raimondi [75] stated that a rate of 0.376 (kg/h)/kW can be assumed as a ratio between the hydrogen flow rate and power for a small hydrogen compressor.

The hydrogen distribution system for automotive uses defined in this study concerns many hydrogen refueling stations in a large territorial area: the entire province of Huesca in the Aragón region. In this scenario, it is hypothesized to build not just a single gasification plant with an attached hydrogen refueling station but a series of plants like that described in Figure 2 to create a mobility network throughout the province. The number of these plants is a result of the optimization of the storage and hydrogen logistic costs, as described below. To consider passenger cars as the intended use for the hydrogen represents the worst economic case respective to heavy duty vehicle utilization: the common level of hydrogen compression required for a passenger car (700 bar) entails a higher cost of installation than for a heavy duty vehicle (commonly 350 bar).

The major cities of the province of Huesca are taken into consideration as places for at least one plant and in particular those cities which represent a cumulative population of at least 50% of the inhabitants of the province. Table 7 shows the biggest cities of the province with the number and percentage of inhabitant compared to the entire population of the province (224,264 inhabitants).

Considering that the gasification system is able to work for 7200 h a year [36] and that it requires four maintenance stops during the year, around two weeks of break every three months are inferred as required for each plant. HRSs obviously also have to allow the refill of hydrogen vehicles when the own gasifier is shut down for maintenance. Each HRS dispenses hydrogen 261 day/year: Saturdays and Sundays are not considered as working days. Hydrogen storage is needed to manage the maintenance period. Limiting the storage is a way to decrease the capital cost: storage is always the most impactful cost in a hydrogen supply chain [74]. A territorial network of gasification plants and HRSs is a way to minimize the capital cost of storage: hydrogen to feed each HRS when its own gasifier is off can be transported via a tube trailer from other running gasifiers as long as there are enough active ones to supply both its own refueling station and another one. Using this approach, it is not necessary to have a stationary storage in each HRS to manage the two weeks of maintenance of the gasifier; only a smaller one is needed to manage the peak hydrogen request on a working day (wd) of a HRS in a year, from Monday to Friday ($wd_{HRS} = 261$ days a year), compared to a continuous 24 h/7 days hydrogen production during the week ($wd_{gasif} = 7200$ h/24 h $= 300$ days a year). For these reasons, each refueling station has both stationary and mobile hydrogen storage.

Table 7. Biggest cities of province of Huesca.

	Inhabitants	% of Province Population
Huesca	53,956	24%
Monzon	17,469	8%
Barbastro	17,174	8%
Fraga	15,353	7%
Jaca	13,129	6%
Total	117,081	53%

3.3. Constrains and Optimization for Sizing

The described case study includes regulatory and technical constrains and a range of values for technical parameters in which to find the optimal solution with a size of the territorial system that minimize the LCOH. The LCOH is defined from field to tank, which means that it includes all the activities from harvesting of biomass in the field to refueling of a hydrogen vehicle at 700 bar.

Figure 3 shows a flowchart summarizing the procedure for sizing and optimizing the system.

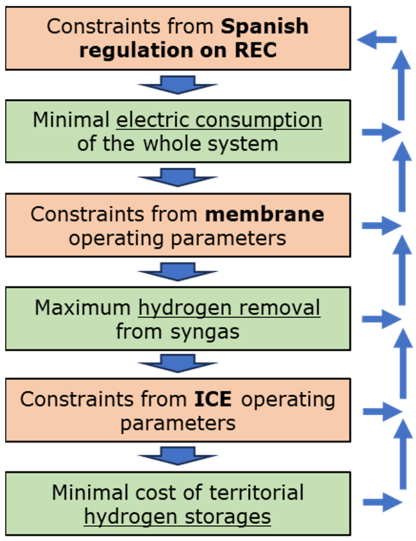

Figure 3. Flowchart for sizing and optimize the system.

As mentioned, the Spanish regulation for a REC allows a simplified payment rule for a renewable power plant with a total energy output at most equal to 100 kW: a direct reduction in the bill due to contemporary produced and consumed energy in the REC and an economic compensation for energy exported and imported in the same month.

In the proposed plant, there are two systems that produce electricity: an ICE burning retentate and a turbine that expands retentate to partially recover compression energy. Their power output is indicated, respectively, as P_{ICE} and P_{tur}. The consumption of electricity for syngas compressor $P_{syn\ comp}$ and for vacuum pump and hydrogen compressors $P_{H2\ comp}$ to store hydrogen at 200 bar defines the total electric output. All these facilities work simultaneously when the gasifier is running, without any variation in the load. The electricity requirements to boost hydrogen pressure at 900 bar for the fast refueling phase are not considered as a continuous need, due to intermittency of that operation. A constrain in the optimal sizing of the basic plant is that the sum of all powers previously considered is equal to 100 kW.

$$P_{ICE} + P_{tur} - P_{syn\ comp} - P_{H2\ comp} = 100\ \text{kW} \tag{5}$$

Based on Spazzafumo and Raimondi [75], the minimal dimension of the REC is defined to assure that electricity produced in the REC E_{prod} of 100 kW net power output is completely valorized, or as simultaneously consumption E_{shared} (that is shared hourly inside the REC) or as economical balancing in each month of the year as exported E_{exp} and imported E_{imp}. In both cases there is a saving on the member's bill. Both conditions can be summarized as follows:

$$\begin{cases} E_{shared} \to E_{prod} \\ E_{imp}v_{pur} - E_{exp}v_{sol} \to 0^{+} \quad \forall\ \text{month} \end{cases} \tag{6}$$

considering values for v_{pur} and v_{sol} as in Equation (2).

This condition maximizes the saving on the bill of REC members, due to electric production in the REC. The size (number of members) of the REC is the unique independent variable: the shape of hourly consumption of the REC is based on lifestyle and seasons, and it is not easily changeable, and the power output is a constant technical constrain both when the gasifier is running and when it is in maintenance (equal to zero). Based on this consideration and on the assumptions described in Section 2.8, the minimal and optimal size is a REC composed of 777 persons grouped into 370 electric domestic passive users. These users have to be at a maximum distance of 500 m from the generation plant to be considered in a single REC, according to the Spanish regulatory framework. Only a configuration inside a city can assure that condition: the Spanish countryside appears too sparsely populated. The monthly distribution of electricity of a modular basic plant in the REC is shown in Figure 4.

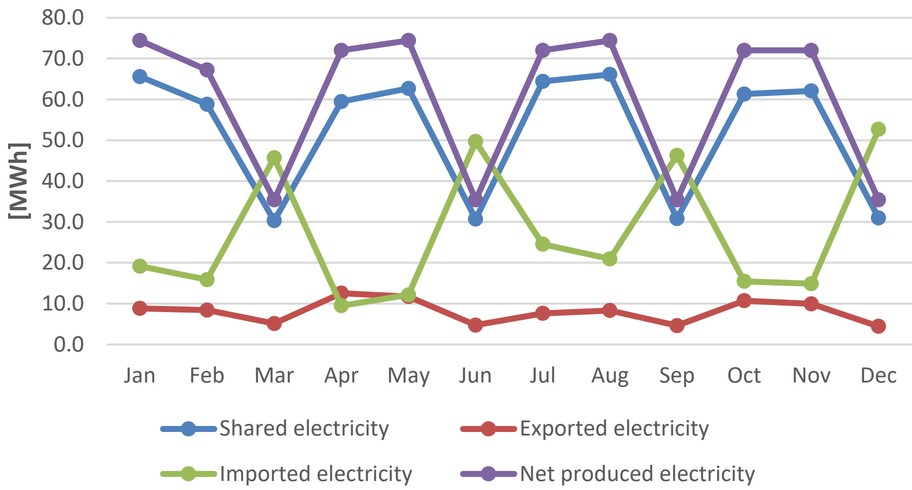

Figure 4. Monthly distribution of electricity in the REC.

March, June, September, and December are the months with two weeks of shut off maintenance for the gasifier.

To optimize the harvesting of energy from retentate a turbine is considered in the study. Its efficiency depends on the inlet pressure [55] that depends on the pressure needed by the membranes and generated by syngas compressor. Given the order of magnitude of flow rates of this study, considering an oil-free compression, the piston Atlas compressor is the best solution, so its outlet pressure defines the solution for the membrane and turbine performances and, consequently, turbine efficiency. The compressor ratio of the chosen Atlas compressor is 15 and, considering pressure drops, the pressure at the membrane is 14.58 bar and at the turbine is 14.3 bar. The temperature of the system is set by two constrains: the exit temperature from the gasifier (600 °C) and the maximum temperature endured by Pd-membranes (500 °C) to allow an acceptable long-life operation. The membrane lifetime chosen in this work is 10 years, since membranes are inside an empty tube and, thus, the conditions are not as extreme as in the fluidized bed. As reported in Section 2.4, the fluidized bed membrane's lifetime can be evaluated to be approximately 9 years. The value of 10 is chosen to be more conservative compared to the value of 15 years estimated for membranes in an empty tube from the literature. With the lifetime of 10 years, only one membrane replacement occurs in the expected 20-year operating period.

These constraints on pressure and temperature in the system define the energy consumption for syngas treatment to allow the membranes to work and also the capability of energy recovery of the syngas turbine: using the chosen solutions for gasification, compression, and Pd-membranes separation, there is no room for optimization via varying thermodynamic parameters.

The hydrogen removal percentage from syngas is a parameter to optimize: the higher the hydrogen removal rate, the greater the efficiency of the system. In the hypothesized scheme, the retentate powers an Internal Combustion Engine originally fed by natural gas. By depleting the syngas of the hydrogen removed from the membranes, the calorific value of retentate decreases: an excessive decrease in this value leads to engine malfunction. Two limits are defined: a retentate LHV at least equal to 3.8 MJ/Nm^3 [59,60] and an ICE derating power output in comparison to methane fed at most equal to 70% [61]. Their variation based on different hydrogen removal percentages in a syngas dried stream are plotted in Figure 5. Considering that the limit on the LHV is never reached for all percentage of hydrogen removal from 0% to 100%, 50% of hydrogen removal is the highest operable value, beyond which deration of the engine power does not allow reliable operation. This constrain means that the highest percentage of hydrogen removal is 50%.

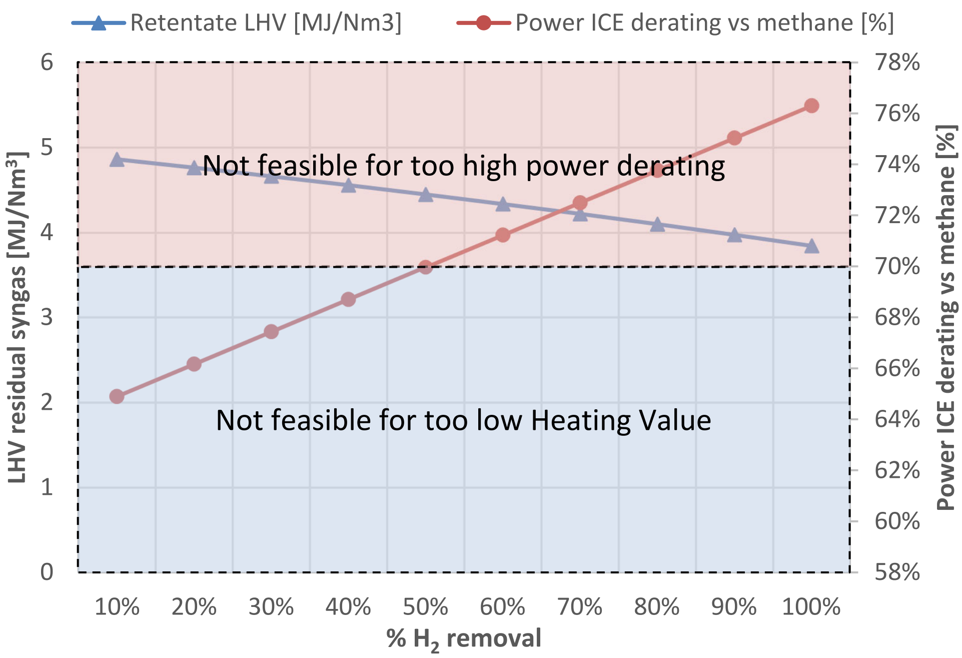

Figure 5. Retentate LHV and ICE derating based on hydrogen removal.

With 50% of hydrogen removal, the weight composition of dry retentate is shown in Table 8 and its specific heats and gas constant are indicated in the last row of Table 3. The retentate LHV is equal to 4.45 MJ/Nm^3.

Table 8. Dried weight syngas composition from membrane (retentate).

CO	H_2	CH_4	CO_2	N_2
22.4%	0.6%	1.3%	17.6%	58.1%

Previous constrains allow us to define the size of the single gasifier and coupled HRS: the proposed RESET gasification system PowerSkid 200+ is able to produce 520.3 Nm^3/h (585.5 kg/h) of dried syngas with a composition as described in Table 6. It consumes 237 kg/h of pruning dried to a moisture composition of 10–15% (12% assumed) and compressed into briquettes. The system produces 16.6 kg/h of biochar. Pd-membranes extract a flow rate $\dot{m}_{H_2}^{ext}$ equal to 89.9 kg/day of hydrogen (3.74 kg/h) over the 7200 h of annual activity. The optimal size of different machines is summarized in Table 9 below.

Table 9. Size of main components.

ICE power output (P_{ICE})	163.1 kW
Syngas turbine power output (P_{tur})	44.9 kW
Syngas compressor power input $(P_{syn\ comp})$	78.1 kW
Vacuum pump and hydrogen compressor power input $(P_{H2\ comp})$	29.9 kW

ICE—Internal Combustion Engine.

The total electricity produced is 720 MWh/year with a shared electricity amount of 623.1 MWh/year. Exported electricity (out of REC) is 96.9 MWh/year and imported electricity 326.7 MWh/year: all exported electricity is compensated economically by value against the imported one. Total economic revenues from electricity are equal to 92,600 EUR/year considering that all savings from REC members are devolved to the REC. A different policy could be actuated, but, in the hypothesis of this study, all revenues are used to facilitate the hydrogen local supply and use chain for mobility.

The total thermal energy harvested from the ICE, compressor, and syngas treatment is equal to 3197 MWh/year (at least at 90 °C): with a 3350 h/year Spanish annual heating period, the heat used in the heating district is 1005 MWh/year (31% of harvested energy). That energy avails 99 flats of around 70 m^2 each, producing an economical revenue of 91,000 EUR/year.

The single system consumes 1706 ton of pruning annually with a total annual cost of 143,600 EUR/year.

Storage of hydrogen is a key factor to allow continuous refueling of vehicles during maintenance stops of gasifiers: minimizing hydrogen storages via optimization of the time management of maintenance stops of gasifier is a key factor to decrease the capital cost of the territorial system proposed. For this purpose, considerations of hydrogen daily flow rates are needed in the running or maintenance mode of the gasifier and in the working or not working condition of the HRSs over the week (it is supposed that in the weekend HRSs are closed). A Pd-membrane hydrogen flow rate $\dot{m}_{H_2}^{ext}$ of 89.9 kg/day over the 7200 running hours produces a total mass of hydrogen per year $M_{H_2}^{year}$ of 26.97 ton/year in each gasifier.

The hydrogen flow rate dispensed in the HRS during weekdays $\dot{m}_{H_2}^{HRS}$ is bigger than the flow rate extracted from the membrane $\dot{m}_{H_2}^{ext}$, due to only five working days a week of the HRS. The hydrogen daily flow rate dispensed by a HRS during weekdays is as follows:

$$\dot{m}_{H_2}^{HRS} = \frac{M_{H_2}^{year}}{wd_{HRS}} = 103.27 \text{ kg/day} \tag{7}$$

where wd_{HRS} is the annual working day of the refueling station and $M_{H_2}^{year}$ is the total mass of hydrogen produced per year by the membranes of a single plant.

From a balancing of mass in a week with gasifier running,

$$7\dot{m}_{H_2}^{ext} = 5\dot{m}_{H_2}^{HRS} + 7\dot{m}_{H_2}^{maint} \quad (8)$$

where $\dot{m}_{H_2}^{maint}$ is the daily flow rate of hydrogen to be stored for the maintenance period, compared to $\dot{m}_{H_2}^{ext}$ that is the hydrogen daily flow rate extracted using the membrane. Consequently, the daily flow rate of hydrogen to be stored for the maintenance period $\dot{m}_{H_2}^{maint}$ can be inferred:

$$\dot{m}_{H_2}^{maint} = \dot{m}_{H_2}^{ext} - \frac{5}{7}\dot{m}_{H_2}^{HRS} = 16.08 \text{ kg/day} \quad (9)$$

When the gasifier is shut down and the HRSs have to dispense hydrogen in daily refueling $\dot{m}_{H_2}^{HRS}$, an amount of hydrogen has to be supplied by the running gasifiers, and the minimal number of required gasifiers n_{min}^{HRS} is

$$n_{min}^{HRS} = \frac{\dot{m}_{H_2}^{HRS}}{\dot{m}_{H_2}^{maint}} = 6.4. \quad (10)$$

Consequently, a group of seven gasifiers ($n_{opt}^{HRS} = 7$) constitutes the optimal territorial system of a provincial hydrogen supply chain. As a result, each gasifier is equipped with a stationary storage $M_{H_2}^{stat}$ to manage the weekly operation and a mobile storage $M_{H_2}^{mob}$ to manage the maintenance of the gasifiers:

$$\begin{cases} M_{H_2}^{stat} = 7\dot{m}_{H_2}^{ext} - 5\dot{m}_{H_2}^{HRS} \cong 120 \text{ kg} \\ M_{H_2}^{mob} = \left(\frac{365 - wd_{gasif}}{4} \cdot \frac{5}{7} \cdot \dot{m}_{H_2}^{HRS} - M_{H_2}^{stat}\right) / n_{opt}^{HRS} \cong 160 \text{ kg} \end{cases} \quad (11)$$

where wd_{gasif} is the annual working day of the gasifier.

Considering the typical minimum inlet pressure for a booster hydrogen compressor [89] and, consequently, a usage rate of the hydrogen stored in a cylinder of 200 bar of around 88%, each basic plant has to be equipped with a hydrogen storage of 140 kg for a stationary one and of 180 kg for a mobile one (results of ratio from results indicated in Equation (11) and 88% of the usage rate). One more mobile storage is necessary for managing logistics among the seven HRSs.

Considering the use of vehicles as stated, each HRS can serve 163 hydrogen passenger cars, consequently a total of 1141 hydrogen cars in the whole province.

A territorial system is summarized as in Table 10 to have a uniform ratio over the cities between the number of RECs and total population of the cities, as well as for the number of hydrogen vehicle per 1000 inhabitants.

Table 10. Characteristic of the provincial hydrogen system.

	REC Number	Ratio Inhabitants on REC Number	Hydrogen Vehicles per 1000 Inhabitants
Huesca	3	17,985	9.1
Monzon	1	17,469	9.4
Barbastro	1	17,174	9.5
Fraga	1	15,353	10.6
Jaca	1	13,129	12.4

REC—Renewable Energy Community.

The total annual hydrogen production is 189 ton/year, consuming 11,900 ton/year of pruning; that is only around 4.5% of pruning annual production from the three most abundant cultivars in the region of Aragón.

3.4. LCOH from "Field to Tank"

In the province of Huesca, as in many areas in Europe, there is no infrastructure for a hydrogen chain (except experimental equipment of Fundación para el Desarrollo de las nuevas tecnologías del hidrógeno in Walqa near Huesca). For this reason, all infrastructure must be erected for production, storage, territorial transportation, and refueling of vehicles. This entails a significant increase in expenditure and, consequently, an increase in the minimum selling price of hydrogen for the sustainability of the initiative. For this reason, the concept of LCOH from field to the tank is introduced: all capital and operational costs from biomass harvesting to hydrogen dispensing at 900 bar are considered. This approach is certainly more unfavorable, but it is the one most in line with those situations in which infrastructure does not exist.

The total cost for all territorial systems (seven gasifiers and seven HRSs) is EUR 14.34 million.

An overview of the capital cost of a single plant is shown in Figure 6.

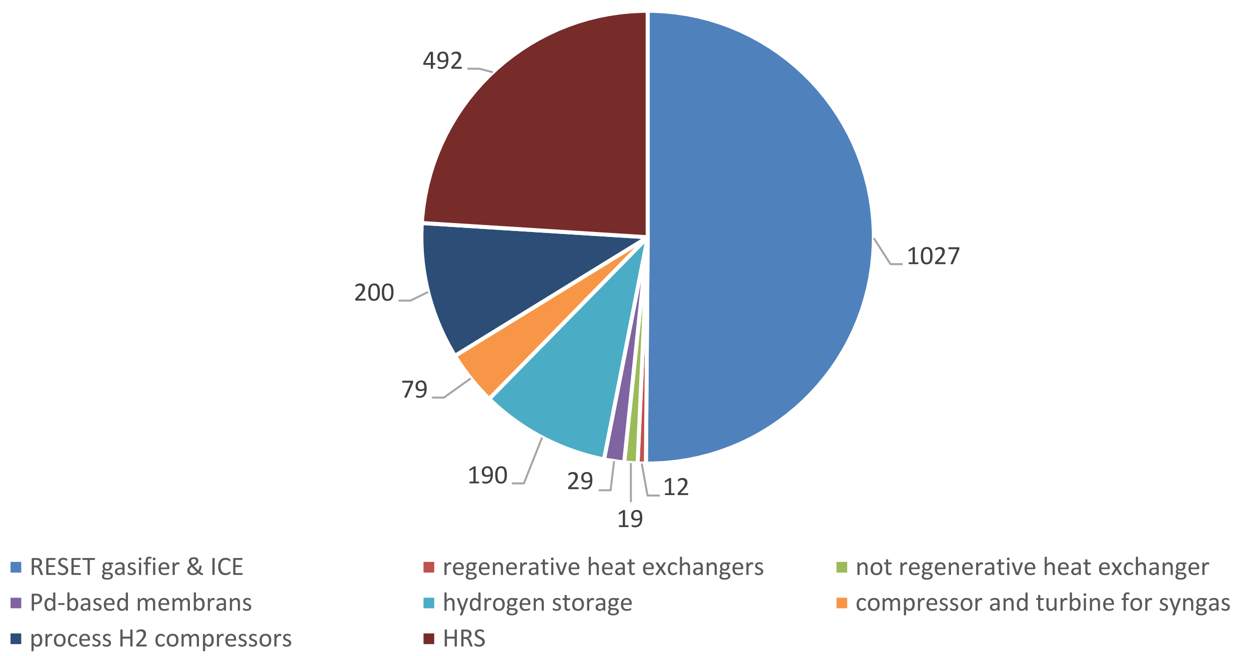

Figure 6. CAPEX overview of a single modular basic plant (values in thousand EUR).

The cost for the gasifier and ICE is the most prominent one, followed by the HRS and process hydrogen compressors to manage the extraction of hydrogen via membranes: these first three entries count for around 85% of total CAPEX. The LCOH is equal to 8.90 EUR/kg—that means a minimum cost of hydrogen at HRS (21% VAT included) of 10.77 EUR/kg. The last value is higher than the hydrogen cost at the HRS (VAT included) that allows the same mileage using a diesel car (6.87 EUR/kg).

The LCOH emerging from the study has been compared with those available in the scientific literature concerning solutions for both producing and dispensing hydrogen, using different feedstocks and technologies [90]. A summary is shown in Table 11.

The territorial hydrogen distribution system proposed in this study seems to increase the LCOH value.

Table 11. Comparison of the LCOH with the literature data (adapted from [90]).

H_2 Production [kg/day]	H_2 Source	H_2 Production Technology	Power Unit Technology	LCOH [EUR/kg]	Ref.
125	water	electrolysis	wind, PV, battery	7.94	[91]
125	water	electrolysis	wind, battery	9.86	[91]
25	water	electrolysis	PV, PEMFC	8.13	[92]
25	water	electrolysis	wind, PEMFC	5.97	[92]
125	water	electrolysis	wind, grid	5.64 to 7.98	[93]
60	water	electrolysis	hydro, grid	9.2 to 15.7	[94]
200	water	electrolysis	PV, grid	9.29	[95]
450	water	electrolysis	PV, grid	7.92	[90]
70	ammonia	cracking/PSA	-	8.06	[96]
200	ammonia	cracking/Pd-membrane	PEMFC	7.35	[97]
100	ammonia	cracking/Pd-membrane	SOFC	9.78	[98]
450	ammonia	cracking/Pd-membrane	PEMFC	6.28	[90]
450	ammonia	cracking/Pd-membrane	SOFC	6.89	[90]
100	biogas	ATR/WGS/Pd-membrane	SOFC	11.23	[99]
450	biogas	ATR/WGS/Pd-membrane	SOFC	7.25	[90]
630	lignocellulosic biomass	Gasification/Pd-membrane	ICE, turbine	8.90	this work

ATR—Autothermal Reforming; ICE—Internal Combustion Engine; PEMFC—Proton Exchange Membrane Fuel Cell; PSA—Pressure Swing Adsorption; PV—Photovoltaic; SOFC—Solid Oxide Fuel Cell; WGS—Water–Gas Shift.

3.5. Sensitivity and Further Development

The most prominent cost is the gasifier and ICE cost, which represents the highest part in the overall CAPEX for the whole plant. It is also affected by high variation, as stated in Figure 8.3 of the IRENA report [77], in Europe in the range of 0–5 MW. A minimum value of 2800 EUR/kW can be considered the best realistic scenario.

Field pruning harvesting costs can be decreased: in normal cultivation operations, pruning on the ground must be treated using a passage of a mechanical means, which generates a cost for the farmer equivalent to the harvesting cost assumed in the scenario of this study (first row of Table 1). Consequently, that value is a fixed operational cost for the farmer, which cannot be attributed to the valorization of the biomass like that described in the study. In view of this consideration, a lignocellulosic biomass harvesting and transformation cost of 44.1 EUR/ton can be inferred.

Considering only these two variations in economical parameters, a LCOH of 3.90 EUR/kg is obtained, with a minimum cost of hydrogen at the HRS (VAT included) of 4.72 EUR/kg, which is largely competitive with diesel. A total investment cost of EUR 11.02 million is required in this case.

Another margin for improvement lies in the valorization of harvested process heat. In fact, only around 30% of that heat is valorized in district heating: if the gasifier is installed near a SME operating with heating requests all year (i.e., laundry or dairy), this percentage could easily be raised to benefit the initiative.

Biochar valorization is not contemplated in this study: future studies could consider it as a revenue stream. Biochar valorization is a controversial matter due to its potential content of polycyclic aromatic hydrocarbons (PAHs). PAHs could be a risk for human health as well as the environment when biochar is used as soil amendment [100], which is one of the most common valorization chains in an agricultural context. An industrial market opportunity for biochar could be reached, but a more detailed chemical analysis is necessary, which is out of the scope of this work.

All aspects that lead to a LCOH lower than the cost of diesel create the opportunity for a revenue for members of the REC, increasing the social acceptability of the initiative.

4. Conclusions

This study develops a techno-economic assessment for a network of modular energy plants fed by residual lignocellulosic waste biomass from farming in Huesca province of

Aragón Region (Spain). The purpose is to generate, at the same time, different energy carriers to be used locally in a Renewable Energy Community (REC). Each plant is based on the gasification of local pruning and contemporary production of power, heat, and hydrogen. Power and heat meet the residential needs of the REC's members, while hydrogen is used for mobility purposes. The considered gasification system is a carbon-negative technology, due to its production of biochar, which traps carbon in its matrix. The plants supply heat and electricity exclusively for proximal RECs; hydrogen is used both for hydrogen refueling stations (HRSs) adjacent to the plant and for others HRSs in the network during the shutdown of gasifiers in the maintenance period, via mobile storage (tube trailer).

The main findings of the present study can be summarized as follows:

- Technologies in the commercial or pre-commercial stage are available to allow the proposed scenario, alongside the whole chain;
- The production and integration of multiple energy carriers allow for better valorization of the residual local lignocellulosic waste material;
- Using local pruning as feedstock in a supply chain not in competition with a food one but in support of it is valuable;
- Renewable Energy Community in Spain is a legal framework enabling new opportunities for local valorization of territorial underutilized resources such as pruning (residual agricultural waste material);
- Incentives given to shared energy in renewable energy communities may trigger the creation of new mobility based on renewable hydrogen;
- The territorial approach, as an alternative at the single plant, allows a significant reduction in costs, especially due to hydrogen storage needs;
- The proposed system allows us to obtain social and territorial advantages, not easily monetizable as job creation, abatement of local pollution by zero-emission hydrogen vehicles and local district heating, and conversion of cost for agricultural waste management into positive economic value.

Using a 100 kW electricity output plant, to be compliant with the simplified economic management system such as the Spanish REC framework, a single modular basic plant is able to satisfy the electricity requirements of 777 persons grouped into 370 electric passive domestic users, with thermal annual needs of 99 flats of around 70 m^2 each and 163 hydrogen cars (with a mileage for each vehicle of 15,000 km/year). An optimal territorial network is composed of seven plants in the five larger cities in the Huesca province: Huesca, Monzon, Barbastro, Fraga, and Jaca. Seven HRSs cover around 50% of inhabitants of the Huesca province. Total biomass consumption is 11,900 ton/year of pruning—that is around 4.5% of pruning annual production of the three most abundant cultivars in the Region of Aragón. The Levelized Cost of Hydrogen (LCOH) is equal to 8.90 EUR/kg and, consequently, a minimum cost of hydrogen at the HRS (21% VAT included) of 10.77 EUR/kg. The LCOH considers all the costs from pruning harvesting to hydrogen refueled in a car at 700 bar (from field to tank) in a territory without hydrogen HRSs. Sensitivity analysis shows the actual possibility to obtain a LCOH at 3.90 EUR/kg.

In the study, economic valorization of the biochar is not taken into account due to checks on the environmental compatibility of biochar produced using the gasification technology considered: a future development could highlight a positive impact on the LCOH.

Given the possibility of the RED II European directive of creating RECs throughout all Europe, the proposed study can be easily adapted to the different regulatory contexts of the states belonging to the European Union, obtaining similar results.

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Abbreviations

ATR	Autothermal Reforming
CHP	Combined Heat and Power
CP	Concentration Polarization
CPC	Concentration Polarization Coefficient
HSR	Hydrogen Refueling Station
ICE	Internal Combustion Engine
LHV	Lower Heating Value
Pd	Palladium
PSA	Pressure Swing Adsorption
PVPC	Voluntary Price for Small Consumers (as for the Spanish acronym)
REC	Renewable Energy Community
RED	European Renewable Energy Directive
RD	Real Decreto (Royal decree)
SME	Small and Medium Enterprise
TEU	Energy component of the access tariff (as for the Spanish acronym)
WGS	Water–Gas Shift

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