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A potential coupling of reforming and electrolysis for producing renewable hydrogen from landfill gas

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Abstract. Organic sold waste disposed of in landfills undergoes a mostly anaerobic process which generates a mixture of methane (CH4), carbon dioxide (CO2) and other various gases such as nitrogen, oxygen, sulphides, and non-methane organic compounds (NMOC), known as landfill gas (LFG). Being composed mostly of CH4 and CO2, landfill gas is a potent greenhouse gas (GHG*)*. As a result, various waste treatment interventions are required to minimize the potential catastrophic damage to the environment from direct greenhouse gas emissions from landfills. One effective solution is combustion to generate electricity exploiting methane's flammability properties. Biomass-based power plants have been present for decades. However, the combustion process is accompanied by a remarkable production of thermal energy which is typically not exploited and therefore lost to the ambient. The current work presents an energetic solution to manage organic waste by employing green hydrogen production. To do so, a hybrid layout based on a cogeneration unit (CHP) fed with landfill gas is considered. The electrical power produced by the CHP is used to produce hydrogen through low-temperature water electrolysis. Furthermore, due to the significant waste heat available in the system, excess thermal power is employed for the methane steam reforming process through a heat recovery section. Hydrogen produced from the reforming section is green since the input is from landfill gas, which is considered renewable. The levelized cost of hydrogen produced from such a hybrid layout is obtained and compared with non-renewable sources in this field. In addition, the annual H2 production rate is calculated for a capacity factor equal to 70%. The results show an annual Hydrogen production of about 167 t/y. LCOH at the stack of about 2 €/kg is reported.

1. Introduction

Organic solid waste disposed of in landfills undergoes a mostly anaerobic decomposition process which results in the formation of landfill gas (LFG), the composition of which varies with respect to the waste composition, temperature, and water content. LFG volume composition is generally 40-60% CH4, 40-50% CO2, but it also presents a 2-5% composition of N2 and H2O, and traces of NMOC (Non-Methane Organic Compounds) [1]. Direct LFG emissions from landfills must be limited for safety reasons, CH4 concentration in the air must not exceed 1% in the landfill and 5% in the air near landfill boundaries [2], and environmental reasons, given that CH4 is a potent GHG, 28 times more than CO2, during a 100-year period [3]. In 2021, in the United States alone, MSW landfills were the third human-related methane-emitting source in the world, accounting for about 14.3% of the total methane emissions [4]. Following the increasing world population projected to reach 8.5 billion in 2030, 9.7 in 2050 and 10.4 by 2100 [5], an increase in the MSW generation is also to be expected, starting from 1.3 billion metric tons in 2010, reaching 2.2 billion metric tons by 2025 and 4.2 by 2050 [6]. The current literature concerning MSW is focused on alternatives to landfills for MSW treatment such as incineration, pyrolysis, and gasification, for what concerns thermal treatments, and anaerobic digestion and composting for what concerns biological treatment [7,8]; EPA, however, estimates that landfills will keep emitting LFG for 10-20 years after closure [9], meaning that LFG treatment in landfills will be a crucial activity for the decarbonization of the MSW sector. LFG is currently treated in-situ, via flare burning or via recovery and exploitation of its energy content in the so-called LFG-to-energy processes. The most diffuse LFG-to-energy processes are: direct electricity production, via a genset or a CHP; medium-btu gas, in which LFG is directly used as fuel source; and finally high-btu gas, by removing the CO2 making LFG suitable for being injected in the natural gas grid [8,10]. The EU has provided the guidelines for the energy transition, for the building sector, through the NZEB and EPBD directives [20] and for the industrial and transport sector, by means of the FitFor55 package [11], which includes all the aforementioned sectors and is based on the reduction of net greenhouse gas emissions by at least 55% by 2030. To reach the objective, several strategies need to be implemented, starting from a complete infrastructural renovation, from the current centralized energy generation to a decentralized energy generation system, with a massive implementation of renewable energy sources (RES) coupled with different type of storage systems. Furthermore, a switch from the sectorial point of view to a holistic one, for what concerns energy sectors, is needed, and can be achieved via the Smart Energy Systems (SES) approach. Such an approach is based on the combination and coordination of the electricity, thermal and gas grid, in order to utilize the synergies between them, to maximize efficiency and reduce overall costs [1,12–17] One of the key drivers of the energy transition is hydrogen produced by RES, known as green hydrogen, which can be exploited in several ways, such as blending with natural gas in the gas grid, with a volume concentration as high as 20%, without any significant risk [16], with a consequent reduction of the natural gas consumption [18]. Furthermore, hydrogen can be used in high-temperature industrial processes, in the chemical industry for ammonia and methanol production, in the mobility sector by direct utilization in fuel cell vehicles or by synthesis of electro-fuel to allow its use in existing vehicles. This last use of hydrogen is promising for the decarbonization of heavy transport [16]. In this context of increasing MSW production and need to rapidly decrease GHG emissions and introduce hydrogen into the energy mix, the present work proposes a solution that combines these aspects via a waste-to-hydrogen (WTH) plant, that can produce green hydrogen starting from MSW disposed of in landfills, with a competitive LCOH, compared to other hydrogen production technologies, while offering a massive decarbonization of the waste sector. The WTH plant proposed in this paper was evaluated through its annual hydrogen production and the LCOH it achieves, as well as the IRR and ROI indexes as a function of the H2 selling price. Lastly, a breakdown of the LCOH, with respect to each component was performed, both for the current (2023) techno-economic assumptions and for the ones forecasted for 2030.

2. Materials and methods

The WTH plant is composed of a CHP, an LFG upgrading and reforming section and an alkaline electrolyser and was simulated using the MATLAB/Simulink software, recreating each component and its interaction with the others, and hypothesizing a capacity factor equal to 70%. A simplified version of the model is reported in figure 1. below. The output of the model is the annual hydrogen production, necessary to calculate, together with the techno-economic assumptions reported in the tables below, the LCOH of the WTH plant, which is the aim of this paper.

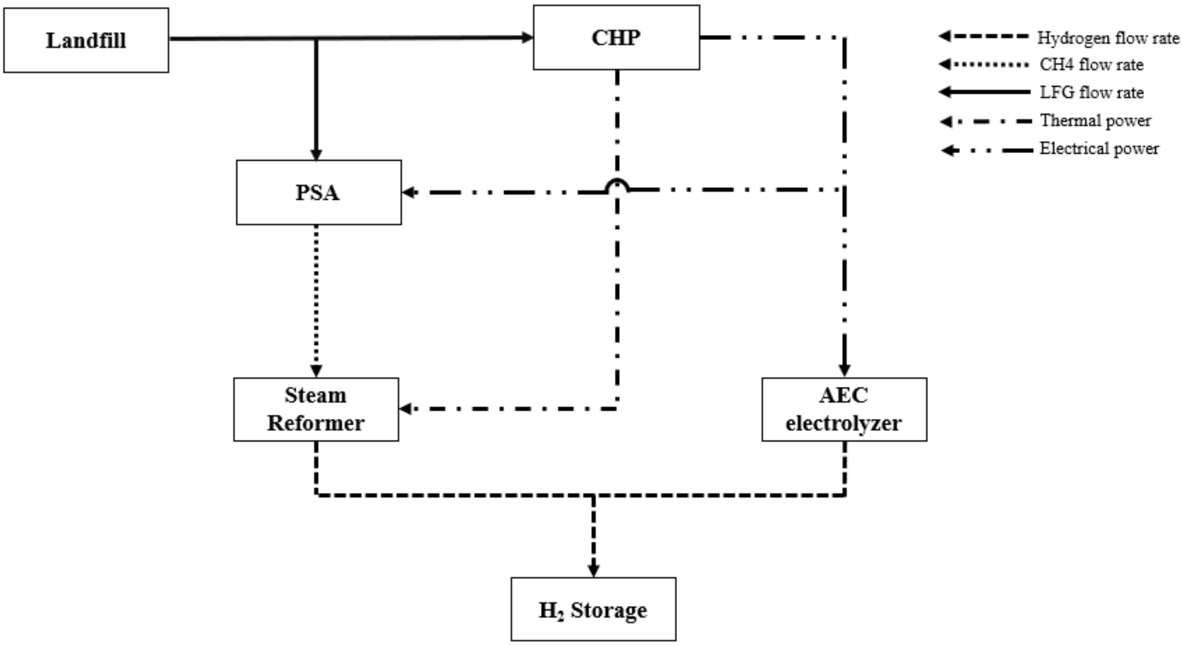

Figure 1. The configuration of the Waste-To-Hydrogen plant

The CHP produces the thermal power needed by the steam reforming section of the plant and the electrical energy needed by the electrolyser and the upgrading section. For the latter, pressure swing adsorption, using zeolite materials was the chosen method. The thermal power produced by the CHP was calculated by multiplying the LFG flow rate and its LHV and the CHP thermal efficiency. The thermal power needed by the reformer was calculated starting from the steam reforming reaction and a considering a steam to methane ratio equal to 2. As a result, the thermal power needed by the steam reformer and the thermal power produced by the CHP, both as a function of the LFG flow rate, are obtained. To ensure these thermal powers are equal, a MATLAB code, which provided the quota of LFG to be fed to CHP and the quota to be fed to the upgrading and reforming section, was run.
The LCOH was calculated using the following equation [13,15].

$$\mathrm{LCOH} = \frac{\mathrm{CAPEX}*\mathrm{crf} + \mathrm{OPEX_y}}{\mathrm{H2_y}}$$

Where:
CAPEX is the total investment cost (CApital EXpenditure),
crf is the capital recovery factor,
OPEXy is the annual operation and maintenance cost,
H2y is the annual hydrogen production by mass.

For what concerns the different components of the plant, the following techno-economic assumptions [21] were made.

Table 1. The efficiency of each component.

Component	Efficiency (%)
CHPth	45
CHPel	40
PSA	98
SR	70
AEC	63

Table 2. Size of each component.

Component	Size	Unit of measurement
CHP	1332	kW
SR	648	kW
PSA	89.96	Nm3
AEC	108.6	Nm3/h

Table 3. Economic assumptions for each component.

Component	Unit	Specific capital cost	Specific O&M cost	Lifetime
CHP	€/kWe	950	9.5	15
PSA	€/Nm3	10400	12.8	20
SR	€/kWH2	820	38.5	25
AEC	€/kWe	950	19	20

3. Results and discussion

The WTH plant was sized with a nominal LFG flow rate of about 600 Nm3/h; 396 Nm3/h (66%) are directly fed to the CHP and the remaining 204 Nm3/h (34%) are fed to the reforming and upgrading section. A simple representation of the WTH plant, together with the energy and mass balance, is reported in figure 2.

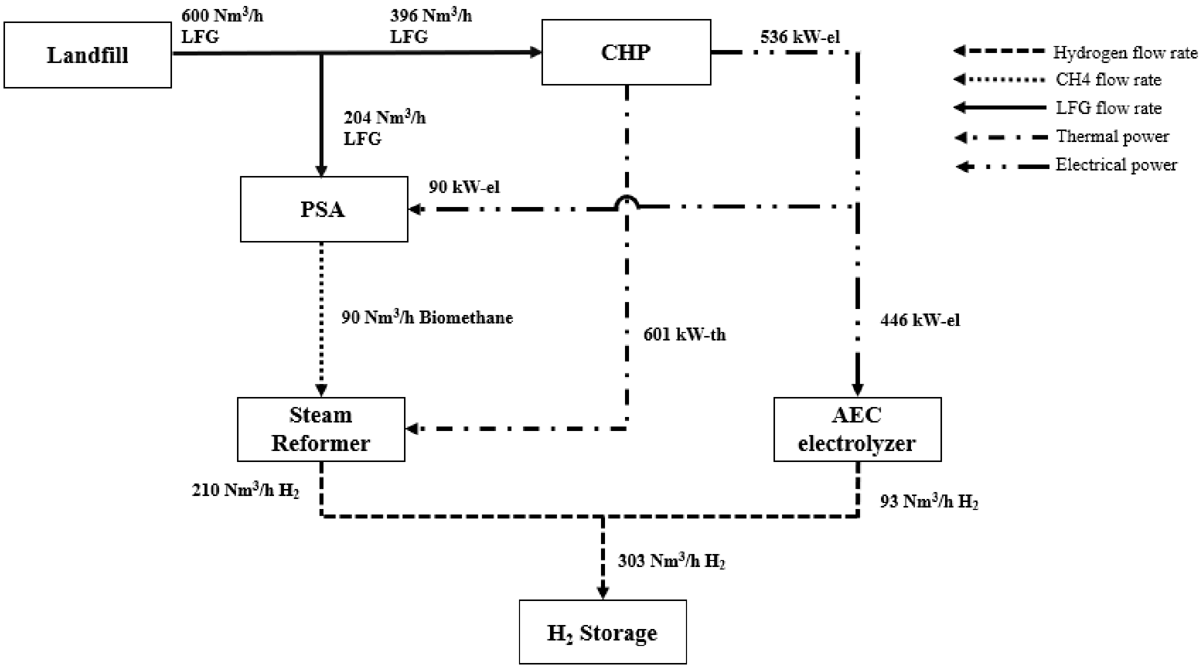

Figure 2. The configuration of the Waste-To-Hydrogen plant and the relative mass and energy balance.

The Waste-To-Hydrogen LFG treating plant proposed in this paper is able to produce about 167 metric tons per year of green hydrogen, with an LCOH of about 2 €/kgH2. Such an LCOH is comparable to non-green hydrogen production technologies, such as grey and especially blue, which have an average LCOH of, approximately, 1.9 €/kgH2 and 2.5 €/kgH2, respectively. Other green hydrogen production technologies, on the other hand, such onshore wind, offshore wind, and PV, have an average LCOH of, approximately, 6.6 €/kgH2 [19]; which makes the WTH plant extremely convenient from the economic point of view. Such a low value of the LCOH provides a decisive acceleration to the learning curve of green hydrogen production, rapidly increasing its diffusion in the energy mix on an international scale.

In order to assess the economic performance of the WTH plant, besides its LCOH, two other parameters have been considered, its internal rate of return (IRR) and its return on investment (ROI), both as a function of the hydrogen selling price. The graphs for the IRR and the ROI as a function of the hydrogen selling price are reported in figure 3 and figure 4, respectively.

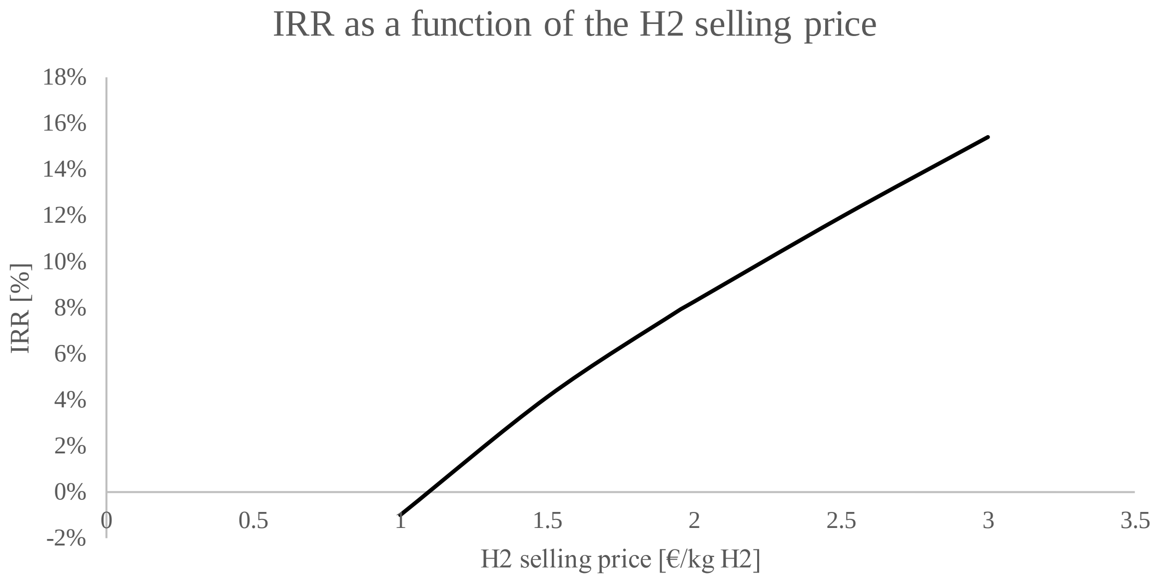

Figure 3. Internal rate of return (IRR) of Waste-To-Hydrogen as a function of the H2 selling price.

The IRR is defined as the interest rate at which the net present value (NPV) of the investment is equal to zero. The IRR which corresponds to an NPV equal to zero is about 7.79% and is obtained by considering an H2 selling price equal to the LCOH of the plant. For values of the H2 selling price greater than the LCOH, meaning IRR values greater than 7.79%, the NPV of the investment is greater than zero.

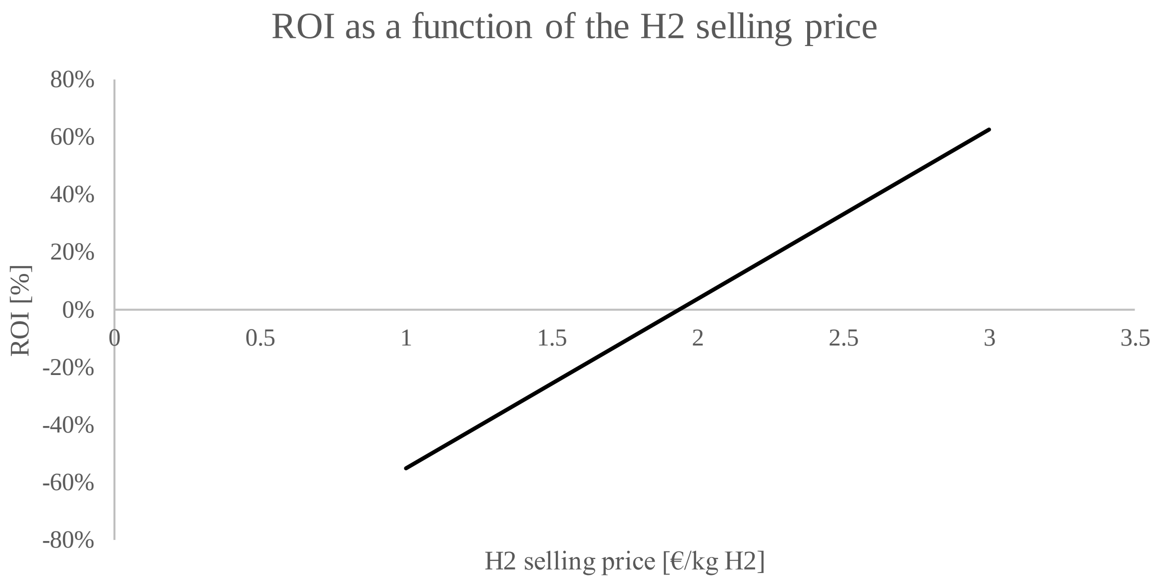

Figure 4. Return on investment (ROI) of Waste-To-Hydrogen as a function of the H2 selling price.

The return on investment (ROI) is defined as the ratio between net income and investment. Negative values for the ROI, are of course, obtained considering an H2 selling price lower than the LCOH, positive values of the ROI are obtained considering an H2 selling price greater than the LCOH and a ROI value equal to zero is obtained considering an H2 selling price, equal to the LCOH. The ROI index clearly shows the profitability of the WTH plant for values of the H2 selling prices in the range of grey and blue hydrogen production technologies and lower than common green hydrogen production technologies.

Finally, in the following two subsections, a sensitivity analysis on the LCOH with respect to the capacity factor, and a breakdown of the LCOH with respect to each component as of today (2023) and in the near future (2030), are reported, respectively.

3.1. Capacity factor

A sensitivity analysis of the LCOH as a function of the WTH plant capacity factor has been carried out and is reported in figure 3. With a capacity factor value going from 10% to 30% the LCOH decreases significantly from just under 14 €/kgH2 to just over 4.5 €/kgH2. By further increasing the capacity factor from 30% to 100%, the LCOH keeps decreasing, however at a much slower rate, going from about 4.5 €/kgH2 to about 1.4 €/kgH2. The capacity factor of the WTH plant assumed in the present study was 70% which provides an LCOH of about 2 €/kgH2. In figure 5, are also reported the values of the capacity factor that the WTH plant would need to achieve to have an LCOH equal to the average LCOH of green, blue, and grey hydrogen production technologies. Such values are, 20%, 50% and 70%, respectively.

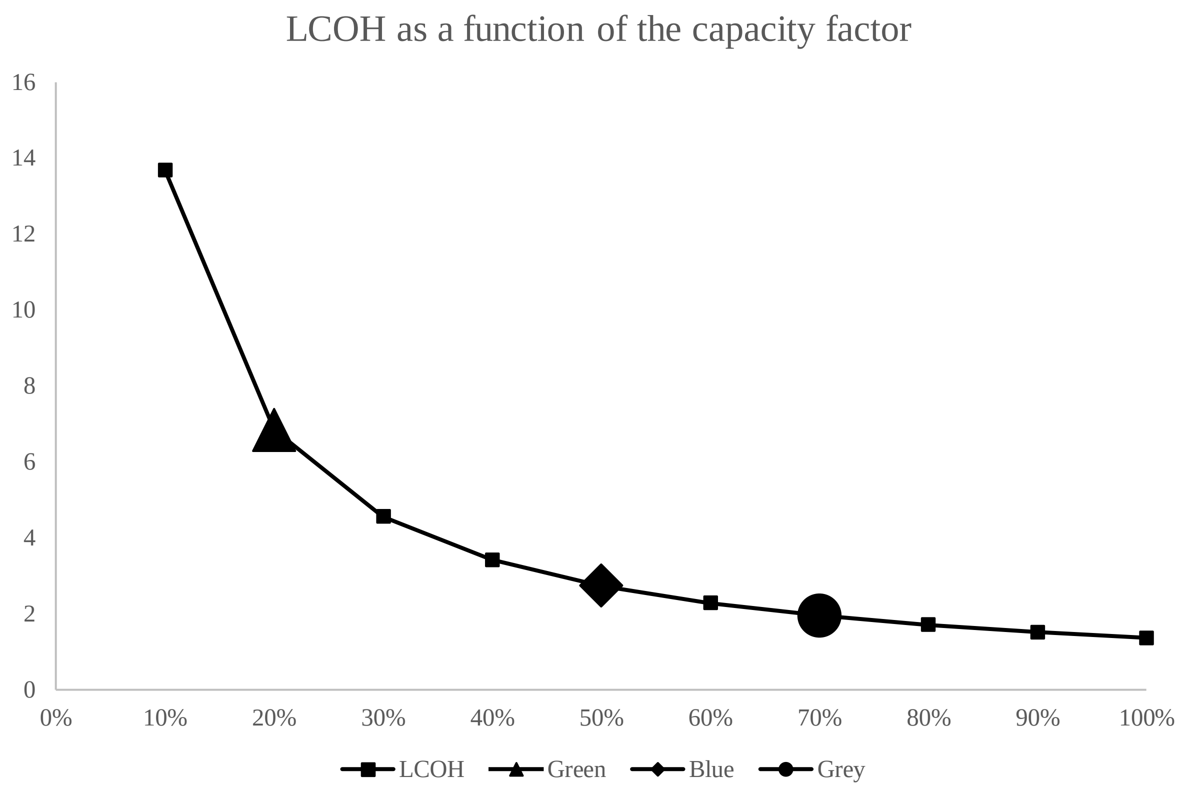

Figure 5. LCOH as a function of the capacity factor.

3.2. Future scenario

The 2030 Scenario has been developed according to the assumptions found in the literature [19] which mainly consist in a reduction of the CAPEX of the cutting-edge technologies considered in the WTH plant. In figure 6, the LCOH breakdown of the WTH plant, with respect to each component, is depicted. In the 2030 forecast, values of the LCOH of about 1 €/kgH2 are feasible. The electrolysers' CAPEX is greatly reduced in this forecast, therefore its impact on the final hydrogen production cost is very low. In both cases, a large part of the cost is due to the PSA and steam reforming unit. On the contrary, the costs for the CHP do not strongly affect the final LCOH. Even a large reduction in the installation cost of components does not allow for production costs below 1 €/kgH2. These values can still be competitive with current hydrogen production costs of PtG based systems. Nevertheless, some recent studies forecast hydrogen production costs below €2/kgH2 as early as 2030 and around €1/kgH2 by 2050 [19].

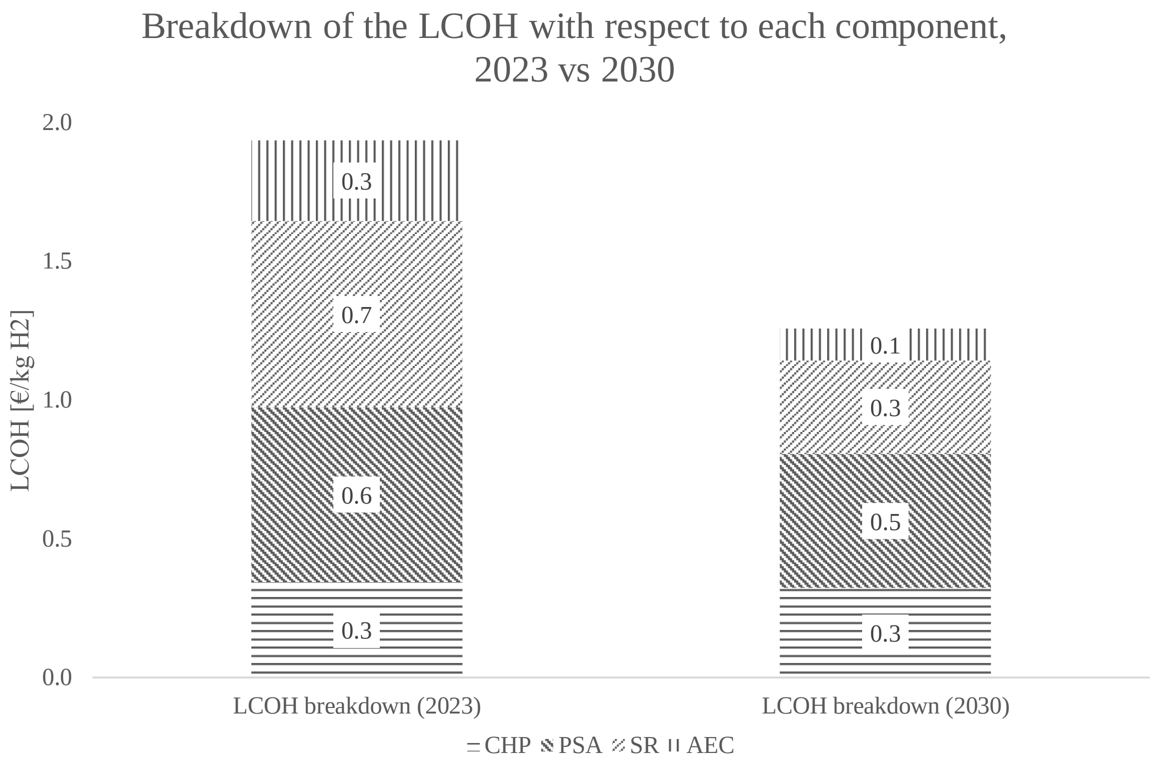

Figure 6. Breakdown of the LCOH with respect to each component, 2023 vs 2030.

4. Conclusions

The aim of the present work is to assess an innovative hybrid system for producing hydrogen from landfill gas combining low temperature water electrolysis and biogas reforming. Alkaline electrolysis and traditional steam methane reforming were the hydrogen production technologies of choice. Pressure swing adsorption (PSA) was the chosen landfill gas upgrading method. Finally, a CHP was implemented, to produce all the thermal and electrical power the Waste-To-Hydrogen plant requires. A case study, characterized by 600 Nm3/h of landfill gas production with an assumed CH4 volume fraction of 45%. The WTH plant performance was evaluated by the levelized cost of hydrogen (LCOH) it achieved, as well as internal rate or return (IRR) and the return on investment (ROI), both as a function of the H2 selling price. Furthermore, a sensitivity analysis on the capacity factor of the WTH plant was carried out, highlighting which capacity factor the WTH plant would need to obtain in order to match the average LCOH of green, blue, and grey hydrogen production technologies. Lastly, a breakdown of the LCOH, with respect to each component of the WTH plant was presented for the current situation (2023) and for the near future (2030).

The results showed that producing green hydrogen by implementing a Waste-To-Hydrogen landfill gas treating plant, as the one proposed in this paper, with an LCOH that is comparable to current grey and blue hydrogen production technologies and lower than current green hydrogen production technologies is feasible. Furthermore, landfill gas is considered a renewable energy source, its complete exploitation by the CHP means that both the thermal and the electrical energy produced are renewable and therefore the hydrogen produced by the WTH is 100% green. The WTH plant proposed in this paper proves that green hydrogen production utilizing 100% of the renewable thermal and electric power generated can be a viable and interesting solution for biomass-based power plants to valorize the waste management systems while simultaneously acting towards its complete decarbonization.

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