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Solar Driven Syngas Production Potential in Portugal

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Abstract. The production of synthesis gas, or syngas, from the thermochemical conversion of different carbon-based feedstocks, including biomass, is an important alternative for the conversion of waste from sources such as agroforestry or urban waste into renewable gases or fuels. The use of solar radiation as an energy source for these thermochemical processes can reduce or even eliminate their environmental impacts and increase the energy content of the resulting syngas. Portugal, with its high levels of solar radiation, has significant potential for solarized syngas production through biomass gasification. This paper analyzes the cost competitiveness of solar-driven syngas production in Portugal using different feedstocks and solar radiation levels and compares these costs to conventional gasification costs. The results show that solarized syngas production in Portugal is economically viable and has the potential to contribute to a more sustainable and low-carbon energy system.

Keywords: Solar-Driven Thermochemistry, Gasification, Biomass

1 Introduction

Used directly or recombined with other carbonaceous sources, syngas stands as a flexible and storable energy carrier with the potential to be delivered in the form of gaseous or liquid fuel to combustion processes (e.g. in industrial burners or internal combustion engines) or further converted to electricity upon recombination with oxygen in a fuel cell (e.g. in the Residential or Transportation sectors).

When produced through the use of GHG emission free renewable energy sources syngas presents the potential for:

- enabling the decarbonization of “hard to abate” sectors where electrification is not a viable option: energy intensive combustion driven processes in Industry or long distance road, rail, maritime or aerial freight transportation, standing today for about one-third of global energy related GHG emissions [1].
- transforming fossil fuel importing regions into renewable energy exporters, as production of syngas stands for the gasification of thereby distributable renewable energy resources.

The composition of H_2/CO ratio as syngas depends on the feedstock, gasifying agent, and operating condition. Several feedstocks, i.e., natural gas, coal, and biomass have been studied for producing syngas. Traditionally, natural gas is used to produce H_2-rich syngas as feedstock in different chemical processes [2]. The most common processes of syngas production from natural gas are steam reforming and dry reforming. Nevertheless, the drawbacks of steam reforming and dry reforming processes are: the high energy requirements of the endothermic reaction in the reformer and; the easy occurrence of coke formation resulting in deactivation of the catalyst [3].

Biomass is a potential energy source for syngas production via renewable resources, as it is relatively abundant and CO_2 neutral, thus enabling the substitution of fossil fuels as feedstock. In the scope of this article, "Biomass" stands for the biodegradable fraction of products, waste and residues from agriculture (including vegetable and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste. It is considered a renewable, eventually carbon neutral and widely available energy source stemming from photosynthesis. The Portuguese territory is very rich in lignocellulosic biomass: 36% of the mainland area is covered by forests, 31% by shrublands and 9% by vineyards, olive and fruit trees. The Portuguese net primary production - the amount of carbon fixed by plants and accumulated as biomass each year – was calculated as 7.5 ton C/(ha.year), roughly doubling the average global biomass productivity, amounting to 3 to 4 ton C/(ha.year). Table 1 shows an estimation of the overall alternative biomass resource with potential to syngas production.

Table 1. *Availability of alternative biomass resources in Portugal*.

Feedstock	**Production (MTon/year)**	**Availability (MTon/year)**	**Obs.**
Forest (F)	135.3	19.1	Roundwood, shrubs, tree residues, by-products of processing industries and recovered post-consumer
Agriculture (A)	1.2-1.6	0.8	Mainly pruning residues from vineyard and olive trees
Solid Urban Waste (SUW)	1.2-2.0	1.0	Not recycled paper/cardboard, plastics, wood and green wastes. Not composted biowastes

The main process of conversion of biomass to syngas is gasification. The gasifying agents, such as air, steam, carbon dioxide, are vital factors that have influence on the syngas yield and process performance. The utilization of steam can enhance the syngas yield, while the use of oxygen can help to supply the necessary heat for the endothermic reactions in the coal and biomass gasifiers [4].

Gasification, as other thermochemical processes, such as pyrolysis, combustion or fermentation, is an autothermal process in which partial use of the feedstock for process heat is carried out, decreasing the final Low Heat Value (LHV) of the syngas produced. In fact, one can define the energetic upgrade factor, U, ratio of the heating value of the syngas produced to that of the feedstock processed

$$U = \frac{m_{syngas} LHV_{syngas}}{m_{feedstock} LHV_{feedstock}} \tag{1}$$

where m_{syngas} and $m_{feedstock}$ are the mass flow in kg/s. Naturally, for autothermal processes $U < 1$, and usually U = 0.75–0.85 depending on the feedstock and process conditions [5].

A possible alternative is to incorporate an external energy source, providing the necessary energetic requirement for the process to take place. In this sense, solar energy, namely Concentrated Solar Power (CSP), is an interesting choice as not only it can provide high-density energy flux as well as achieve the necessary high-operating temperatures. Literature shows that the incorporation of such systems on thermochemical processes leads to a gain on syngas LHV value [6] (*U* > 1). Amongst all CSP technologies, Central Tower Receiver is the common choice for such high-temperature thermochemical processes, having efficiencies solar-to-heat above 40%. This technology achieves very high concentrations (typically between 500X-2500X) and, if adequaded materials are used, it has been proven that it could be able to achive 800ºC or even beyond [7].

Today, syngas levelized cost (LCOS) for biomass gasification is around 0.54 €/kg, or around 0.37 €/kWh in view of the syngas calorific value [8]. Solar-driven gasification can then be competitive if the additional solar CAPEX cost is compensated by a valorization of the LHV of the syngas. In this work a techno-economic analysis is carried out under the major assumptions:

- A single-step biomass gasification process at 800ºC with a *U* between 0.7-0.8.
- Incorporation of a 1100 m^2 Central Tower Receiver (CTR) with a mean conversion solar-to-heat of 49.3% and a daily operation fraction, D_f = 70% [7];
- A mean value of U_{solar} = 1.25. In fact, this parameter may vary during the operation but for the sake of simplification it was considered as a reasonable choice. Of course the higher the U_{solar}, the better performance is achieved [5].
- Four different locations were considered in the analysis: Berlin (Germany), Évora (Portugal), Hurghada (Egypt) and Atacama (Chile) with values of DNI (Direct Normal Irradiance) of 990 kWh/m^2/year, 2142 kWh/m^2/year, 2696 kWh/m^2/year and 3155 kWh/m^2/year, respectively.
- Project lifetime of 20 years, discount rate of 7%, inflation of 3%, feedstock cost of 0.04 €/kg, OPEX of 4% of CAPEX and residual value of 5% of CAPEX.

In the next sections a detailed description of the implemented methodology and outputs are presented.

2 Techno-economic model and results

The conditions for the gasification process are shown in Figure 1.

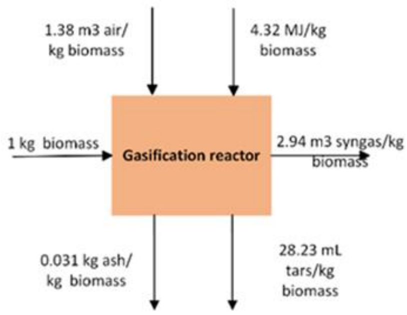

Figure 1. *Gasification process conditions and outputs*.

The energetic requirements and syngas output are shown in Table 2.

***Table 2**. Gasification energetic requirements and syngas outputs*.

Feedstock	Energy requirements for gasification (kWh/kg)	Volume syngas ($m^3/kg_{feedstock}$)	LHVfeedstock ($MJ/kg_{feedstock}$)	LHVsyngas ($MJ/kg_{feedstock}$)
Forest [9]	1.4	2.94	18.4	5.3
Agriculture [10]	1.2	2.62	18.2	5.4
SUW [11]	1.5	3.02	19.0	4.9

Solar-driven gasification implies the incorporation of the energy input coming from the CTR system, corresponding to a total amount of annual consumption of biomass and respective volume of syngas, as shown in Table 3.

***Table 3.** Solar-driven energetic output, annual consumption of biomass feedstock and respective annual volume of syngas produced*.

Location	DNI ($kWh/m^2/year$) [12]	Annual useful energy (E_{solar}) (MWh)	Annual consumption of biomass ($c_{feedstock}$) (ton/year)			Annual volume of syngas produced (ha.m/year)		
			F	A	SUW	F	A	SUW
Berlin	990	376	265	313	251	78	82	76
Évora	2142	813	573	678	542	168	178	164
Hurghada	2692	102	720	852	681	212	223	206
Atacama	3155	120	843	998	798	248	261	241

From the values on Table 3 it is possible to design the process conditions, namely the mean daily number of hours of operation of the gasifier and pyrolysis reactor (t_{day}). This was done considering the location of Évora as reference, targeting a value of U between 0.7-0.8. Due to the energetic input difference from each location, t_{day} had to be adjusted for each case to ensure the same value of U.

Setting a value of t_{day} = 6h to Évora location (considering that the gasifier only works with the solar-driven system), it is possible to estimate the mean value of $m_{feedstock}$ by:

$$m_{feedstock} = \frac{c_{feedstock}}{365 * D_f * t_{day}} \quad (2)$$

Considering the conditions of the thermochemical processes and the experimental results from literature, it is possible to set up the conditions for each location ensuring that U is the same for each feedstock, as shown in Table 4.

***Table 4.** Gasifier outputs*.

Loc.	t_{day} (h)	$m_{feedstock}$ (kg/h)			m_{syngas} (kg/h)			$U_{gasifier}$			LHV syngas (MJ/kg)		
		F	A	SUW	F	A	SUW	F	A	SUW	F	A	SUW
Évora	6	374	442	354	1035	1089	1006	0.8	0.73	0.73	5.3	5.4	4.9

Having considered a specific weight of 0.94 for the syngas. For Berlin, Hurgahda and Atacama tday is 3h, 8h and 9h, respectively, keeping the same $U_{gasifier}$ and LHV value. Notice that the value obtained for $m_{feedstock}$ is adjustable to what can be found in the market for gasifier systems, where consumptions rates up to 1000 kg/h (depending on the type of feedstock) can be found [13].

Considering now the U_{solar} = 1.25 one can estimate the amount of upgraded syngas LHV and the total amount produced as a difference between the final and initial LHV value, as shown in Table 5. Again, Évora is used as reference as the result is the same for the other location by the adaption of the t_{day} value.

Table 5. *Upgraded syngas production.*

U_{solar}	LHV upgraded syngas (MJ/kg)			Upgraded syngas produced (kWh/year)		
	F	A	SUW	F	A	SUW
1.25	8.3	9.2	8.4	48056	71667	52222

Solar-driven can then be competitive if the additional solar CAPEX cost is compensated by a valorization of the LHV of the syngas. Figure 2 shows the LCOS for different locations under the macroeconomic assumptions mentioned in the Introduction section.

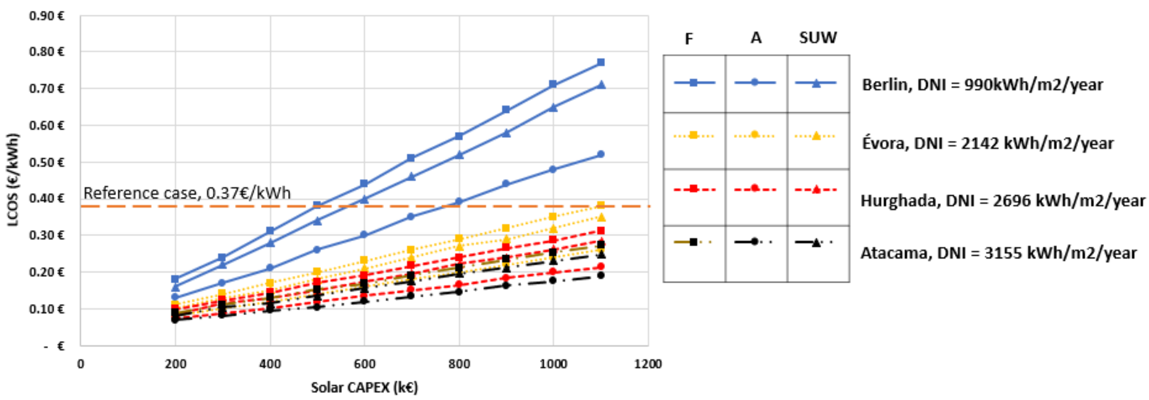

Figure 2*. LCOS for 4 different locations: Berlin, Évora, Hurghada and Atacama. For each location, the LCOS calculation was done for each feedstock considered: Forest (F), Agriculture (A) and Solid Urban Waste (SUW).*

The results show that in the majority of the cases the LCOS is below the reference case, which confirms that the solar CAPEX investment is clearly compensated by the energetic upgrade of the syngas produced. No further economic assessment, namely business case model, was considered in this study has it is a preliminary assessment of the potential of solar-driven gasification processes.

Taking as a reference the LCOS value of 0.37€/kWh for the non-upgraded syngas (conventional gasification, LHV = 5.3 MJ/kg considering forestry residues) as taking into account the CAPEX related with the gasification reactor and auxiliaries, one can estimate overall solar-driven syngas (LVH = 8.3 MJ/kg considering forestry residues) production in Évora to be in the range of 0.28 to 0.37 €/kWh.

3 Potential production in Portugal and preliminary competitiveness assessment

From Table 1 and Table 5 it is possible to estimate the potential overall energetic production of upgraded syngas in Portugal. These results are shown in Table 6.

Table 6. *Expected yearly syngas production in Portugal*.

Feedstock	Availability (MTon/year)	Annual volume syngas (ha.m/year)	Upgraded syngas annual energy (GWh/year)
Forest	19.1	5615	122
Agriculture	0.8	210	5.1
SUW	1.0	302	6.6

Wheres this potential is sizeble, still must be considered as a modest when compared to the energy production assets existing and foreseen to the Portuguese energy system (a similar energy yield might be expected from a 75MWp PV power plant in Portugal).

On the other hand, upgraded syngas costs are still far from being competitive with e.g. green H_2 to which Portugal has defined a national strategy (EN-H2 [14]), whose production costs range today between, roughly, 2-5 €/kg and, by 2050, are expected to be reduced to values ranging, roughly, 1-3.5 €/kg (0.03-0.09 €/kWh, respectively, considering a value of 39 kWh/kg) [15].

Not standing for a significant energy potential nor for a competitive energy source (depending on many external requirements to achieve the ideal effect), the conversion of residues into renewable syngas might be regarded, though, as a waste treatment/valorization strategy. Upon such an approach, additional revenues could be considered, such as a waste treatment service tariff supporting the production of syngas from such feedstock sources. At present, residue treatment service related revenues which could be turned into such approach might be found:

- In the residue treatment levy currently in place after the portuguese DL n.º 102-D/2020 [17] and standing for 25 €/Ton in 2023, rapidly increasing to 35 €/Ton in 2025, whose gasification would stand for a 80% discount;
- An annual cost wildfire fight/prevention amounting to 529 M€/year, in 2022 [18].

Table 7. *Syngas production incentives for different sources of revenues*.

Feedstock	Annual syngas energy production (GWh)	Annual revenue	Maximum syngas production incentive (€/kWh)
Forest	122	529 M€	4.34
Agriculture	5.1	16M€ - 22M€ (0.8 MTon at 80% of 25-35 €/Ton)	3.13 – 4.31
SUW	6.6	20M€ - 28M€ (1.0 MTon at 80% of 25-35 €/Ton)	3.03 – 4.24

The results presented in Table 7 clearly indicate a potential for the the implementation of a “service based” strategy for a competitive exploitation of alternative biomass residues from the different sources considered: the use of less than 10% of the identified revenues would suffice the funding of such strategy.

4 Conclusions and next steps

This work conducted a preliminary assessment of the potential of syngas production in Portugal via solar-driven biomass gasification process. The results show that the incorporation of a solar field to new or already existing gasification processes can be cost-competitive, due to the energetic upgrade (LHV) of the syngas generated, achieving values below the reference of 0.37 €/kWh.

Solar-driven syngas must be competitive with other energy vectors such as green H_2 or biomethane. Due to its relatively low energetic content, syngas tends to have a higher cost €/kWh when compared to those alternatives. As the potential to increase the value of syngas LHV is rather constrained (reactor's physical limitations, useful contribution of solar energy input etc.), this competitiveness must be achieved via other paths such as feed-in tariffs and valorization of absence/reduction of negative externalities due to the use of biomass waste as feedstock: better forest/agriculture management, lower water consumption, creation of new market possibilities, etc. Not standing for a significant energy potential nor for a competitive energy source, the conversion of residues into renewable syngas might be regarded, though, as a waste treatment/valorization. The use of currently existing financial resources stemming from e.g. residue treatment levies or wildfire prevention/fight costs might seemighly enable the implementation of a national strategy around this concept.

Out of the scope of this article, biomass can alternatively be converted into syngas via:

- pyrolysis, by means of slow pyrolysis (5 to 30 minutes) [5] favoring the production of biochar and syngas (production of biochar will be maximum at lower temperature - maximum yield at 300°C and will decrease with higher temperature but the syngas production will then increase);
- hydrothermal liquefaction (HTL, also known as hydrous pyrolysis), a thermochemical depolymerisation process in an enclosed reactor to convert wet biomass into biocrude oil and chemicals at moderate temperature (typically 200–400°C) and high pressure (typically 10–25 MPa) [19].

Considering all these possibilities, the authors will focus their attention of the deeper development of the economic model considering all the possible energy vectors, envisaging the use of syngas on a "x-to-x" approach, seeking the increase of the economic competitiveness of such solution and possible experimental demonstration pilots in Portugal.

This analysis will consider other thermochemical processes mentioned, such as pyrolysis and HTL, envisaging the operation at lower temperatures than gasification (between 250-550ºC) considering the use of Molten Salts (MS) as heat transfer fluid ans its associated thermal storage system. This approach will take advantage from the current use of MS in CSP systems, hence aligned with the solar-driven approach presented in this work.

Author contributions

Conceptualization: PH, DC, CA, PB, RP. Data curation: DC, CA, RP. Formal Analysis: PH, DC, RP. Funding acquisition: PH, PB. Methodology: PH, DC. Supervision: PH, CA, PB. Visualization: DC, RP. Writing – original draft: PH, DC. Writing – review & editing: PH, DC, CA, PB, RP.

Competing interests

The authors declare that they have no competing interests.

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