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# Modelling a Hydrogen Production System using Solar Hierarchical Volumetric Receivers and a Steam Gasification Reactor

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The use of solar energy in the production of fuels is a compelling and attractive application, as it can mitigate issues related to the intermittency of solar energy, thereby supporting the transition to a low-carbon economy. For instance, excess solar energy collected during the day can be used to produce hydrogen, which can then be utilized in the evening or at night to generate electricity or heat. This work addresses a numerical investigation of hydrogen production by steam gasification of biomass, assisted by concentrated solar energy. Air, heated by an innovative hierarchical volumetric receiver installed on a solar dish, powers the steam gasifier. To estimate the hydrogen production, experimental data provided by a parabolic dish with a diameter of 8.6 m, a volumetric receiver, and a lab-scale fixed-bed steam gasifier were used. The gasification reaction was simulated assuming thermodynamic equilibrium. Computational experiments show that hierarchical volumetric receivers can be used to sustain hydrogen production by steam gasification of biomass. In particular, the results point out that the integration of such solar volumetric receivers in steam gasifiers can lead to a significant production of hydrogen, 3.4 tonnes/year, and of carbon monoxide, 15 tonnes/year. Moreover, the use of solar energy is able to mitigate 20.3 tonnes of carbon dioxide emissions equivalent per year.

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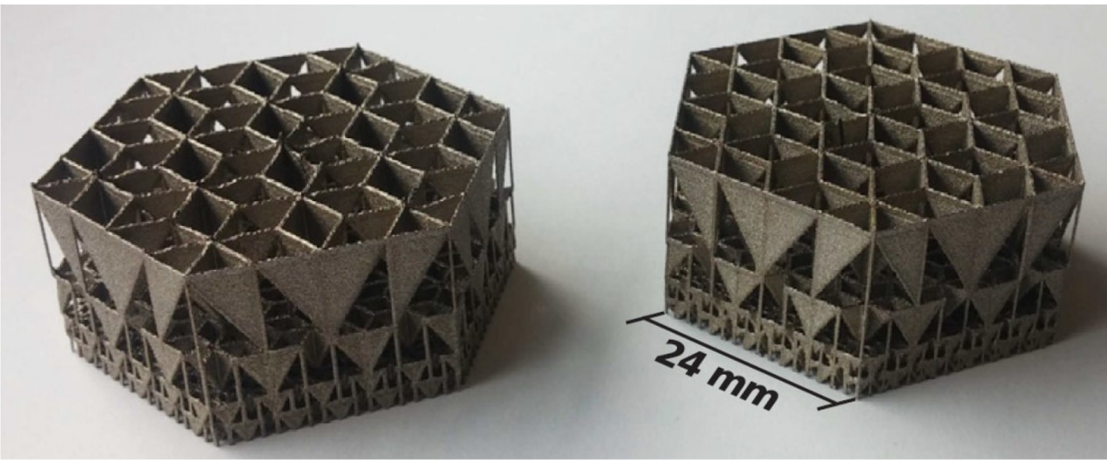
## S1 Solar dish and volumetric receiver

**S1a** Solar dish located in Rovereto (Italy), 8.6 m diameter, DNI 1000 W/m2 power on target 44 kW, target diameter 20 cm. Two tracking axes, angular resolution less 0.1 degrees.




**S1b** The hierarchical-layered volumetric receiver is conceived in modular hexagonal elements manufactured in stainless steel (AISI 316L) by selective laser melting. Selective laser melting (SLM) is a 3D printing technology that allows the creation of complex-shaped objects by successive melting of metal powder using a controlled laser beam. The geometry of the receiver is built from the fractal repetition of elementary cells. The elementary cell consists of a rhombic prism with partially opened walls that allows the flow redistribution between the near cells. The elementary cell is replicated to create a hexagonal-shaped layer.





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## S2 Estimation of the efficiency of Hierarchical Volumetric Receivers (HVRs)

Thermal efficiency = 73.2%
Incident heat = 510 W
Air temperature rise = 285.8 K
Air inlet temperature = 400 K
Air outlet temperature = 685.8 K
Air outlet temperature / Surface temperature = 0.91
Surface temperature = 750 K
Porosity = 96.04%
Surface area = Area of hexagon x (1- Porosity) = 5.44255 x $10^{-5}$ $m^2$
Solar absorptivity = 0.74

Assuming the thermal emissivity is the same as the absorptivity:

$$\eta_{thermal} = \frac{\alpha\, Q_{in} - \varepsilon\, \sigma\, A_{surface}\, T_{surface}^{4}}{Q_{in}}$$

$$= 73.86\ \%$$

## S3 Techno-economic assessment calculations

The minimum selling price of hydrogen per kilogram, that is the expected hydrogen production cost, is calculated based on the UNIFHY project steam gasifier [1]. The nominal power considered for the solar-driven gasifier is the thermal power received by the air loop at 1000 W/m$^2$, which is around 27 kW$_{th}$. The solar collector nominal power is 44 kW$_{th}$. The hydrogen price evaluation is carried out considering the annual hydrogen production and the hours of sun during the year in Gela (Italy), which is one of the cities with the highest solar irradiation in Italy. A scenario where subsidization by the state on the initial investment is considered, with a reduction of 65% of the CapEx. This value is chosen assuming that the tax deduction dictated by the Italian regulation "Normativa EcoBonus" can be applied [2]. A lifetime of the plant of 20 years is considered, and the cost of capital is set to 7%. The capital expenditure (CapEx) includes the cost of the gasifier, the portable purification system, and the cost regarding the design of the plant and its construction. The operational expenditure (OpEx) includes maintenance cost, insurance cost, feedstock cost, and the cost of the electric energy consumption of the auxiliaries.

The techno-economic assessment of the solar-driven gasifier (*SolarGasif*) is carried out applying an exponential scaling of the annual CapEx based on the nominal thermal power, using the UNIFHY gasifier as a reference [3]:

$$CapEx_{SolarGasif} = CapEx_{UNIFHY} \cdot \left(\frac{P_{th,\,SolarGasif}}{P_{th,\,UNIFHY}}\right)^{0.6}$$

Where $P_{th}$ is the nominal thermal power.

For the total CapEx of the CSP collector, a reference value of 1600 €/kW was considered [4].

The annual CapEx of the system was then calculated applying a cost of capital of 7% on a time span of 20 years:

$$CapEx\,[€/year] = CapEx[€/20years] \cdot \frac{0.07}{1-(1+0.07)^{-20}}$$

The maintenance cost is proportionally scaled considering the nominal power and the annual operational hours of the solar-driven gasifier and the UNIFHY gasifier [3]. The following formula is applied:

$$OpEx_{\substack{Maint,\\ SolarGasif}} = OpEx_{\substack{Maint,\\ UNIFHY}} \cdot \frac{AOH_{SolarGasif}}{AOH_{UNIFHY}} \cdot \frac{P_{th,\,SolarGasif}}{P_{th,UNIFHY}}$$

Where $AOH$ is the value of annual operating hours.

The insurance costs are evaluated scaling the insurance costs of the UNIFHY gasifier proportionally, according to the nominal power:

$$OpEx_{\substack{Insur,\\ SolarGasif}} = OpEx_{\substack{Insur,\\ UNIFHY}} \cdot \frac{P_{th,\,SolarGasif}}{P_{th,UNIFHY}}$$

The total cost of the electricity is estimated considering a cost per kWh of 0.08€ [1] and for the OpEx of the CSP collector the value 0.01 €cent/kWh was considered [4].

Finally, the hydrogen cost per kilogram is evaluated as the ratio of the total annual cost and the annual hydrogen production.

## Notes and references


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[2] ENEA - Dipartimento Unità per l’efficienza energetica, ‘INTERVENTI DI RISPARMIO ENERGETICO E UTILIZZO DI FONTI DI ENERGIA RINNOVABILE’, DETRAZIONI FISCALI - Ecobonus, Superbonus e Bonus casa. Accessed: Sep. 20, 2024. [Online]. Available: https://www.efficienzaenergetica.enea.it/detrazioni-fiscali.html

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