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# Environmental assessment of a HYSOL CSP plant compared to a conventional tower CSP plant

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## Abstract

The aim of this paper is to evaluate the environmental performance of a Concentrating Solar Power (CSP) plant based on HYSOL technology. The plant under investigation is a solar tower system with 14 hours thermal energy storage using biomethane as auxiliary fuel and using a 100 MWe steam turbine and a 80 MWe gas turbine in the combined cycle (Brayton and Rankine) characteristic of the HYSOL technology. The results evidence that HYSOL technology performs significantly better in environmental terms than conventional CSP. This evidence is particularly relevant in the climate change category where HYSOL plants presents 43.0 kg $CO_2$ eq /MWh. In contrast, the hybrid CSP plant operating with natural gas emits 370 kg $CO_2$ eq /MWh. This difference is attributable primarily to the nature of the auxiliary fuel (biomethane in HYSOL and natural gas in conventional CSP), but also to the higher thermal efficiencies achieved in the HYSOL configuration, which prevents the emission of 106 kg $CO_2$ eq /MWh. The environmental significance of the additional components and infrastructure associated with the Brayton cycle in the HYSOL technology (gas turbine, Heat Recovery System and Low Temperature Energy Storage) are negligible.

*Keywords:* CSP; HYSOL; LCA; solar energy; natural gas; biomethane; carbon footprint.

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## 1. Introduction

Scientific and commercial developments worldwide have proven the technology viability of using concentrated solar energy for the production of electricity at a large scale. However, conventional Concentrating Solar Power (CSP) plants are still criticized for their high costs and inability to produce power on demand. HYSOL is the acronym of a research project lead by the Spanish engineering company ACS-COBRA and funded by the European Commission under its 7th Framework Programme (FP7-ENERGY-2012-1, CP 308912) and the title *Innovative Configuration of a Fully Renewable Hybrid CSP Plant*. The aim of this project is to develop and test a new hybrid configuration for CSP plants intended to achieve higher energy efficiency, reduced economic and environmental costs, and also improved firmness and dispatchability in the generation of power on demand. Furthermore, HYSOL plants would operate using biomethane as auxiliary fuel, resulting in the generation of electricity that is 100 % renewable.

HYSOL plants will be able to work as a peak-load, generating power directly from the sun during the day, using stored solar energy during the night and the gas turbine when the storage system is empty. Additionally, they may also operate as a peak-base, working with both turbines (steam and gas) at the same time. The design and operation of HYSOL can be adapted to the requirements of the location in terms of solar resource availability and also cost and characteristics of auxiliary fuels, which may be of fossil or renewable nature. The HYSOL concept is based on a CSP plant with Thermal Energy Storage (TES) in the form of molten salts, and may be applied both to parabolic trough or solar tower systems. The plant incorporates a Brayton cycle that operates in combination with a conventional Rankine cycle, making use of the thermal energy entrained in the exhaust gases of the gas turbine. By doing so, the plant is able to maximize the share of electricity produced by solar resource and also to optimize the efficiency in the transformation of the auxiliary fuel into electricity, so that power is produced in a dispatchable, firm and efficient manner with optimized fuel consumption [1].

Despite its renewable nature, solar power also generates environmental impacts that need to be identified, quantified and evaluated. Various publications have been dedicated to evaluate the environmental performance and carbon footprint of conventional CSP plants, including those based on tower technology, parabolic trough and also TES [2-6]. These analyses are all based on Life Cycle Assessment (LCA) methodology. The objectives of this investigation are threefold: (1) to evaluate the environmental performance of a CSP plant based on HYSOL configuration; (2) to compare the environmental performance of the HYSOL configuration using natural gas or biogas as auxiliary fuels, (3) to compare the HYSOL configuration against a conventional hybrid CSP configuration producing the same amount of electricity.

## 2. Methodology

### 2.1. Description of the CSP plant

The CSP plant used as a reference in this analysis is based on HYSOL configuration, as developed in FP7-ENERGY-2012-1, CP 308912. Details about the specifications and plant configuration are described in Figure 1 and Table 1 (under the column Reference plant). Power plant characteristics and electricity generation for the HYSOL plant located in southern Spain were calculated and supplied by IDie (Investigación, Desarrollo e innovación energética, S.L.), a Spanish engineering firm. The plant under consideration is based on a combined cycle configuration incorporating a 100 MWe steam turbine and a 80 MWe gas turbine. The solar field (number 1 in Figure 1) is based on tower technology and consists of 9151 heliostats presenting a surrounding layout. The solar radiation reflected by the heliostats is directed to an external central receiver (2) increasing the thermal energy contained in a Heat Transfer Fluid (HTF). This HTF consists of binary nitrate molten salts and fulfils two objectives: transporting the heat to the steam generation system, and storing thermal energy using TES. HYSOL configuration comprises a 14 hours indirect two-tank TES (3) used to support dispatchability and increase electricity generation. The thermal energy gathered by the HTF is subsequently used to drive the thermodynamic Rankine cycle (4) based on air cooling technology for reduced water consumption (at the expense of lower electricity generation efficiencies and higher economic costs). The aero derivative gas turbine (5) consumes biomethane as auxiliary fuel and it is used to support electricity generation when thermal storage is empty or to increase electricity generation at peak-base. Exhaust gases from the gas turbine are driven to a Heat Recovery System (HRS) where the HTF is reheated (6), thus improving fuel utilization efficiency and storage dispatchability. Electricity generation, adapted to the Spanish electricity demand curve, has been calculated to amount to 928,620 MWh/yr of gross electricity output; 847,248 MWh/yr of net electricity (which takes into consideration parasitic electricity consumption and efficiency losses); and 797,423 MWh/yr of electricity sold to the Spanish electricity market (which takes into consideration additional efficiency losses due to grid/plant availability and curtailment, and annual degradation of components).

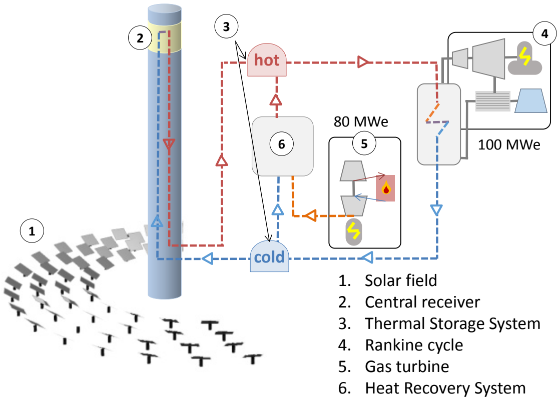

Figure 1 Configuration of the HYSOL plant.

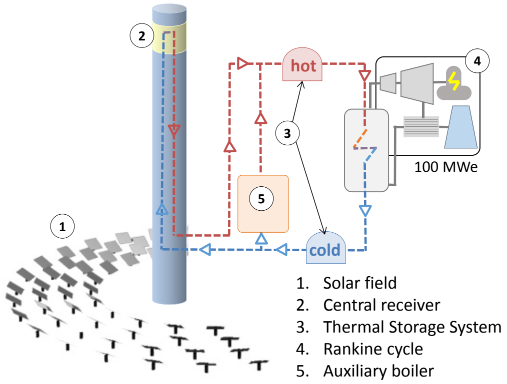

Figure 2 Configuration of a hybrid tower power plant: Scenario B

Table 1 Power plant characteristics and electricity sold to the Spanish electricity market for each scenario.

| Characteristics of the power plant | Reference plant | Scenario A: HYSOL with natural gas | Scenario B: Hybrid CSP with natural gas |
|---|---|---|---|
| Direct Normal Irradiation, KWh/m$^2$ | 2086 | 2086 | 2086 |
| Heliostats, units | 9151 | 9151 | 9151 |
| Aperture, m$^2$ | 1,321,174 | 1,321,174 | 1,321,174 |
| Tower height, m | 201 | 201 | 201 |
| Annual gross electricity generation, MWh/yr | 928,620 | 928,620 | 935,683 |
| Annual electricity sold, MWh/yr | 797,423 | 797,423 | 797,423 |
| Solar fraction, % | 45 | 45 | 46 |
| Thermal cycle efficiency, gas to electricity (%) | 52 | 52 | 40 |
| Consumption of gas, MJ/yr | 3.40E+09 | 3.40E+09 | 4.56E+09 |

The environmental performance of the reference HYSOL CSP plant was compared against two alternative scenarios: (A) HYSOL configuration using natural gas as auxiliary fuel (instead of biomethane), and (B) conventional CSP (no HYSOL) tower plant using natural gas (NG) as auxiliary fuel. The power plant in scenario A has the same characteristics and configuration as the reference plant, while the CSP plant analyzed in scenario B follows the configuration shown in Figure 2. This configuration is based on a conventional CSP tower plant where the auxiliary fuel (natural gas) is used to increase thermal energy contained in the HTF via an auxiliary boiler. It is assumed that the solar field configuration and the amount of electricity sold in scenario B are the same as in the reference plant, which involves the consumption of 1.14E+11 MJ of natural gas, for a solar fraction of 46 %. Specifications of this scenario are described in Table 1 under the column Scenario B.

In scenario A, biogas is produced and injected into the NG grid after being upgraded into biomethane. Biogas facilities placed in different locations within Spain are assumed to provide biomethane to the NG grid, which is subsequently used by the CSP plant. This biogas is produced from biowaste consisting of a mixture of sewage sludge, agri-food waste and pig/cow manure. The standard biogas facility considered consume 26.000 t/year of biowaste for the production of 1.300.000 Nm$^3$/year of biogas through anaerobic thermophilic fermentation.

### *2.2. Scope and inventory*

The LCA was conducted according to standard methods ISO 14040:2006 and ISO 14044: 2006. The functional unit to which all the impacts are referred to is the generation of 1 MWh of electricity sold to the electricity market. The lifetime of the plant has been assumed to be 25 years. The analysis was based on a comprehensive inventory covering the following phases: (1) acquisition of raw materials and manufacturing, (2) construction, (3) operation and maintenance, and (4) dismantling and waste management. Most of the inventory was supplied by IDie and ACS-COBRA. Impact estimations take into consideration extraction of raw materials, manufacturing and transportation of plant components and waste management of components at the end of their lives.

- Material extraction and manufacturing (E&M): This phase takes into consideration extraction of raw materials as well as manufacturing and transportation of plant components. The following elements were considered in the life cycle inventory of the CSP plant:
    - Central receiver system: central tower, receiver, piping and circulation pumps.
    - Solar field: sun collectors (frame, mirrors, foundations), sun tracking system, controls.
    - Thermal storage: piping, tanks, foundations, insulation, heat exchangers, pumps, salts.
    - Power block: components associated with the Rankine steam cycle and the Brayton cycle.
    - Facilities: buildings, roads, water treatment plant.
- Construction (C): This phase includes the use of machinery and the consumption of energy for the construction of the CSP plant. It also includes auxiliary structures and materials used for construction.
- Operation and maintenance (O&M): This phase takes into consideration the vehicles for maintenance operations, water consumption for cleaning mirrors, lubricating oil, consumption of auxiliary fuel, heliostats replacement and electricity generation. It also includes consumption of gas necessary to melt nitrate salts in start-up operations.
- Dismantling and disposal (D&D): Dismantling of the CSP plant and waste management of plant components were considered in this phase. Due to lack of data for dismantling operation, energy and machinery requirements in this stage have been assumed to be the same as indicated in other studies of a similar power plant[7].

EcoInvent v.3 was used to obtain generic environmental information about the following elements: processing of raw materials, manufacturing of plant components, construction activities, operation and maintenance of the CSP plant, and transport processes. It has been assumed that the steam turbine and molten salts pumps are manufactured in Germany, the gas turbine in Italy and the molten salts in Chile. Each component was modelled to be transported by ship to the port nearest to the CSP plant, and by lorry from the port to the plant. Data related to solar field foundations, tower materials and heliostat pedestal materials was not provided to the authors. Thus, inventory data published in studies of similar CSP plants was used in each case [7,8].

The assessment of biomethane production follows a “cradle to grave” approach, starting from the transport of biowaste and ending with its upgrading. The core processes include pre-treatment of biowaste, fermentation and post-fermentation, and upgrading of raw biogas. It also includes as core processes environmental impacts derived from the construction and decommission of the biogas plant and equipments. The lifetime of the biogas plants is assumed to be 20 years. Transportation of the biowaste to the biogas plants, production of auxiliary elements and purchased electricity are modelled as upstream processes. The biowaste used for biomethane production is modelled free of any environmental burdens, since it is a residue derived from other product systems. Additionally, solid and liquid digestate obtained in the processing of biogas is considered as a co-product of the biogas and is returned to the environment in the form of free fertilizer offered to local farmers. It was considered that anaerobic digestion of pig/cow manure was an improved agricultural practice with respect to the conventional treatment (storage in an uncovered tank before field application as fertilizer), therefore the avoided emissions of $CH_4$ and $N_2O$ from the conventional treatment were considered into the study, as described by Giuntoli et al[9]. Environmental impacts derived from the NG life cycle were determined by ecoinvent v3 database, adapting the original CORES data to Spanish NG imports[10] as follows: 69% of Algerian NG, 16% of Nigerian NG, 10.9 % of Norwegian NG and 3.9% of Netherlands NG.

### *2.3. Impact assessment methods*

Simapro 8.0.3 software was used for calculations. Recipe Midpoint World (H perspective) was used for aggregation of environmental impacts. The Cumulative Energy Demand (CED) v9 method[11] was applied to determine primary energy demand for each case. The water stress index was calculated taking into account direct water consumption during the operation and maintenance of the CSP plant and the corresponding regional water stress index published by Pfister et al.[12]. The water stress index, defined as the ratio of total annual freshwater withdrawals to hydrological availability, ranges from 0 (no water stress) to 1 (extreme water stress). The Pfister et al. method implemented in Google Earth[13] indicated a 0.9927 index for the location under study (Talarrubias, Badajoz).

## 3. Results and discussion

Table 2 shows the characterized impacts of the HYSOL CSP plant in the four life phases considered: E&E, C, O&M, and D&D. The selection of impact categories is based both on their environmental significance and also on international environmental concern. These are: climate change, terrestrial acidification, human toxicity, freshwater eutrophication, freshwater ecotoxicity and marine ecotoxicity.

Table 2 Characterized impacts of the reference plant (HYSOL configuration) per impact category and life phase.

| Impact category | E&M | C | O&M | D&D | TOTAL |
|---|---|---|---|---|---|
| Climate change, kg $CO_2$ eq/MWh | 9.80 | 1.79 | 37.7 | -3.35 | 45.9 |
| Terrestrial acidification, g $SO_2$ eq/MWh | 47.6 | 8.41 | 465 | -11.7 | 509 |
| Freshwater eutrophication, g P eq/MWh | 4.21 | 0.44 | 13.0 | -0.80 | 16.9 |
| Human toxicity, kg 1.4-DB eq/MWh | 5.21 | 0.59 | 22.4 | -0.68 | 27.5 |
| Freshwater ecotoxicity, g 1.4-DB eq/MWh | 216 | 19.5 | 792 | 4.71 | 1,033 |
| Marine ecotoxicity, g 1.4-DB eq/MWh | 209 | 19.9 | 797 | 2.76 | 1,028 |
| Cumulative Energy Demand MJ/MWh | 120 | 21.0 | 1,220 | -25.1 | 1,337 |
| Water Stress $m^3$/MWh | - | - | 0.164 | - | 0.164 |

Environmental impacts in the selected categories are as follows: climate change 45.9 kg $CO_2$ eq/MWh; acidification 509 g $SO_2$ eq/MWh; eutrophication 16.9 g P eq/MWh; human toxicity 27.5 kg 1,4-DB eq/MWh; freshwater ecotoxicity 1033 g 1,4-DB eq/MWh; marine ecotoxicity 1028 g 1,4-DB eq/MWh: CED 1337 MJ/MWh; water stress 0.164 m3/MWh. The low emissions obtained for climate change category are due mainly to the use of biomethane as auxiliary fuel, since it includes the environmental benefits associated with the management of biowaste ($CH_4$, $N_2O$ emissions).

Most of the environmental impacts of the HYSOL configuration are attributed to the O&M phase, since the impacts derived from the production and combustion of the auxiliary fuel are higher than those of the manufacturing of power plant components. This pattern of impacts is similar to the one obtained in the life cycle assessment of conventional hybrid CSP plants[14]. The results suggest that the production of biomethane represents between 69 % and 91 % of the life cycle environmental impact on every category, except for water stress whose contribution is 8.4 %. Higher contributions were detected to the CED, human toxicity and climate change categories (92, 84 and 83 %

respectively). Human toxicity impacts for biomethane production are due mainly to the higher electricity consumption during upgrading and biogas generation, since the disposal of mining spoils and uranium tailings (from fossil fuels contributing to the electricity mix) have emissions with high toxicity to humans. Climate change impacts from biomethane production are associated mainly with energy consumption during biogas production and $CH_4$ emissions during the upgrading process.

The CED associated with the life cycle of the HYSOL reference plant was calculated to be 1,337 MJ/MWh. The consumption of external energy (considering the entire life cycle of the technology) represents 37 % of all the electricity sold to the electricity market. O&M is the most energy intensive phase (34 % of the electricity sold) due mainly to consumption of biomethane for power generation, maintenance and start-up operations. This is followed by E&M (3.3 %) due to energy use associated with extraction of raw materials involved in the construction of the plant. Consumption of external energy in the construction (C) and Dismantling and Decommissioning (D&D) phases is very limited (below 1 %).

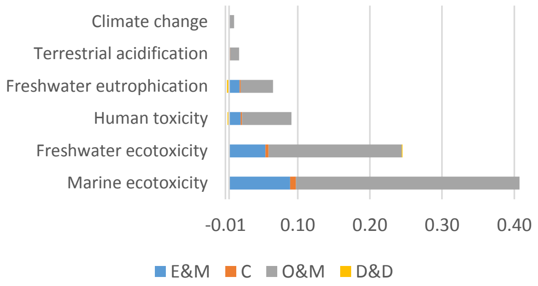

Figure 3 Normalization profile of the reference plant per impact category and life phase.

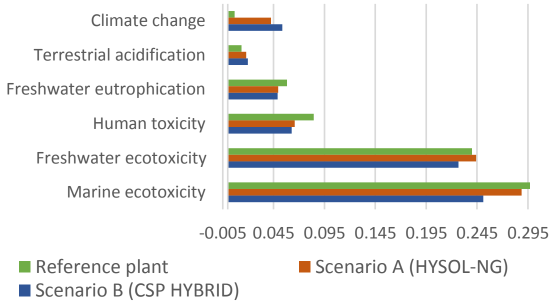

Figure 4 Normalization impact of the reference plant (HYSOL) compared to scenario A (HYSOL with NG) and B (Hybrid CSP).

Figure 3 shows the normalized impacts associated with the reference plant. These results indicate the higher relative impact of the toxicity categories compared to the rest of environmental impact categories. The impact on the human toxicity category is mainly associated with the production of biogas (81 % of the life cycle impact on this category), followed by the manufacturing of heliostats (14 % of impact related to heliostats' materials). Impacts on the marine and freshwater ecotoxicity categories originate primarily from the production of biogas, but also from the extraction and manufacturing of materials and components in the E&M phase of the life cycle of the plant (18% and 23 % of impact respectively is attributable mainly to the use of metals in the heliostats).

### *3.1. Comparison of scenarios*

Table 3 describes the environmental performance associated with the generation of 1 MWh of electricity in the different scenarios contemplated in the study. The results evidence a deterioration in the environmental performance of the CSP plant (per functional unit of electricity) when operating with NG, especially in the hybrid scenario. This deterioration is especially remarkable in the climate change category, whose indicator changes from 45.9 kg $CO_2$ eq/MWh to 294 kg $CO_2$ eq/MWh in scenario A and 392 kg $CO_2$ eq/MWh in scenario B. Variations in other impact categories were less significant. It should be noted that the environmental impact on human and marine toxicity regarding the reference plant is higher than in scenario A. This is due to the higher human toxicity potential of biogas with respect to NG, which is associated with the transport activities during slurry waste management and the materials employed in the construction of the biogas plant. The environmental impact associated with the construction of the Brayton cycle and the HRS required to operate the plant in HYSOL configuration is negligible compared to the total life cycle impacts.

CED results indicate that the primary energy consumed during the life cycle of the power plant in scenario A and B is more than four and six times higher than that of the reference plant, respectively. The difference observed between the reference plant (1,337 MJ/MWh) and scenario A (6,344 MJ/MWh) is attributable to the changes in primary energy demand associated with the life cycle of biomethane and NG. In the case of scenario B (8,484 MJ/MWh), the difference is also due to inferior efficiency associated with the production of electricity by combustion of NG in a single cycle auxiliary boiler, compared with the combined cycle technology.

Table 3 Life cycle characterized impacts of the reference plant (HYSOL) compared to scenario A (HYSOL with NG) and B (Hybrid CSP).

| Impact category | Reference plant | Scenario A: HYSOL with NG | Scenario B: Hybrid CSP with NG |
|---|---|---|---|
| Climate change, kg $CO_2$ eq/MWh | 45.9 | 294 | 392 |
| Terrestrial acidification, g $SO_2$ eq/MWh | 509 | 694 | 891 |
| Freshwater eutrophication, kg P eq/MWh | 16.9 | 14.4 | 17.9 |
| Human toxicity, kg 1.4-DB eq/MWh | 27.5 | 21.4 | 26.8 |
| Freshwater ecotoxicity, kg 1.4-DB eq/MWh | 1,033 | 1,052 | 1,320 |
| Marine ecotoxicity, g 1.4-DB eq/MWh | 1,028 | 711 | 866 |
| Cumulative Energy Demand MJ/MWh | 1,337 | 6,344 | 8,484 |
| Water Stress $m^3$/MWh | 0.164 | 0.151 | 0.161 |

Figure 4 shows a comparative analysis of the normalized impacts in different categories for different scenarios: reference plant (HYSOL), scenario A (HYSOL with NG), and scenario B (hybrid CSP with NG). The results evidence that marine and freshwater ecotoxicity are the categories most significantly affected in all cases, followed by human toxicity. The relative impact on freshwater ecotoxicity is higher in the alternative scenarios than in the reference plant, due to the activities related to the extraction of NG.

## 4. Conclusions

The environmental performance of a CSP plant based on HYSOL technology is significantly better than the one observed for a conventional hybrid CSP plant considering the same net electricity production and similar plant characteristics. This evidence is particularly relevant in the climate change category, since the HYSOL configuration 45.9 kg $CO_2$ eq/MWh while the hybrid CSP plant operating with NG emits 392 kg $CO_2$ eq /MWh. This difference is mainly due to the nature of the auxiliary fuel (biomethane in HYSOL and NG in conventional CSP), but also to the higher thermal efficiencies achieved in the HYSOL configuration. The environmental results of the HYSOL technology operating with NG compared to the hybrid CSP plant indicates that higher thermal efficiencies in HYSOL configuration prevents the emission of 98 kg $CO_2$ eq /MWh, while the impacts of the components and infrastructure associated with the Brayton cycle (gas turbine, HRS and LTES) are negligible.

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