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Life cycle assessment of a concentrated solar power plant for the production of enriched methane by steam reforming process.

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The global energy related challenges, mainly due to the worldwide growing energy consumption gone with a reduction of oil and gas availability, is leading to an increasing interest on hydrogen as energy carrier. Hydrogen could have the potential to reshape the entire energy industry since it can be produced from renewable energy sources and it can be consumed in fuel cells, with a significant reduction of air pollutants or greenhouse gas (GHG) emissions that is a significant reduction of its environmental impact.
Nowadays, the most important tool to evaluate the environmental impact of a product is the life cycle assessment (LCA) that determines the overall impact of a product on the environment. To this aim, several impact categories are defined; among these the most important are the Global Warming, the Abiotic Depletion, the Eutrophication, the Acidification, the Land Use and the Human toxicity.
The aim of this work is to present a the Life cycle Assessment of a novel hybrid plant for the production of a mixture of methane and hydrogen, called enriched methane, from a steam reforming reactor whose heat duty is supplied by a molten salt stream heated up by an innovative concentrating solar power (CSP) plant developed by ENEA. The performance of this plant will be evaluated from an environmental point of view by the use of a LCA software (SimaPro7) and compared with that ones of traditional plants (reformer and cracker for the hydrogen production) for the production of enriched methane.

1. Introduction

The well-known energetic issue is stimulating the development of clean innovative technologies for the reduction of GHG emissions and the creation of a more sustainable economic structure worldwide. In this context, hydrogen is one of the most promising new frontiers to be explored. In fact, hydrogen can be produced by using renewable

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energy sources and can be converted in fuel cells, producing electrical energy without emitting polluting substances. Therefore, enriched methane diffusion as fuel could constitute a crucial step towards a more sustainable economy worldwide. The mixture is composed by methane with a variable content of hydrogen, which can be produced through the use of renewable energy sources.

In order to avoid the well-know problems related to the transport and storage of the pure hydrogen, in this work the hydrogen concentration in the natural gas (NG) has been limited to 17 vol% (HCNG-17) (De Falco et al., 2009; Haeseldonckx and D'haeseleer, 2007). At this concentration, HCNG mixtures can feed natural gas powered internal combustion engines (NG-ICE): a number of papers, appeared in the scientific literature, claim that increasing hydrogen content in the NG engine allows BSFC, BSCO2, BSCO, BSHC to be reduced, improving the engine efficiency and reducing the pollutants emissions (Bauer et al., 2001a, Bauer et al., 2001b; Orhan Akansu et al., 2004; Ortenzi et al., 2008).

One of the most important challenges toward a sustainable development is the minimization of the environmental footprint derived from the hydrogen production processes. Even if hydrogen can be produced by water splitting, using thermo-chemical cycles at low environmental impact, indeed the natural gas steam reforming process is the most important process to produce large amounts of hydrogen.

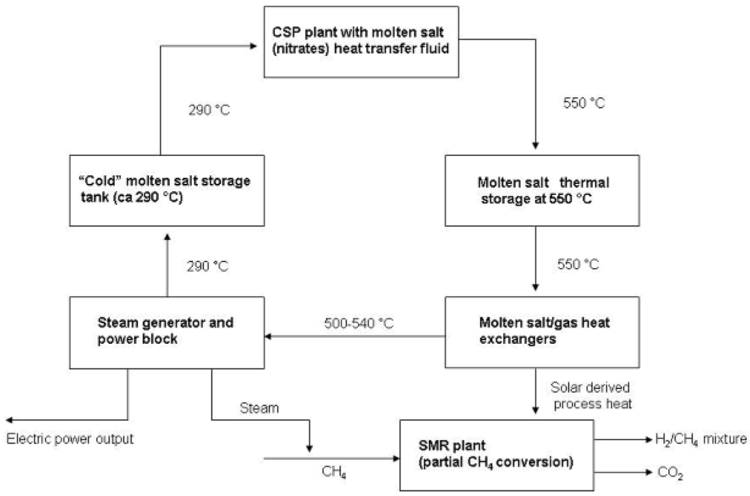

Figure 1: CSP plant flow diagram

The main disadvantages of this process is that the steam reforming reaction is highly endothermic therefore a part of natural gas (methane) feedstock is burned to supply the great amount of heat duty, without producing hydrogen. For this reason, a large amount of CO_2 is emitted as reaction and combustion products (8-12 kg_{CO2}/kg_{H2}).

However, if just a 17 vol% content of hydrogen is requested, a lower operating temperature is needed to limit methane conversion to about 5 %, that is enough to satisfy the specification on the enriched methane composition. As a consequence the

steam reforming process can be efficiently matched with solar-derived heat available at temperatures lower than 600 °C, avoiding the heat generation by hydrocarbons combustion and so reducing the CO_2 emissions. This consideration leads to the idea to couple a steam reforming process for enriched methane production with a 550°C molten salt concentrating solar power (CSP) plant. The CSP basically consists of a solar collector field, a receiver, a heat transfer fluid loop; a suitable heat storage system is also required to maximize the ''capacity factor'' (i.e. productivity) of the solar plant, and to provide solar heat at the desired rate regardless the instantaneous solar radiation availability and fluctuations (Winter et al., 1991; Mills, 2004).
The process scheme is shown in Figure 1. A so designed plant is able to produce clean electrical energy by using the molten salt residual heat from the hydrogen production process, realizing a co-generation process.
The aim of this work is to evaluate the performance of the proposed CSP plant from an environmental point of view by the use of the Life Cycle Assessment Methodology which is based on calculations and analysis of effects to environment, human health, socioeconomic factors and climate change.

2. Methodology

The functional unit of this LCA is defined as 1 Nm^3 of HCNG-17 produced by the hybrid plant. The study is a “cradle-to-gate” LCA. This means, that it mainly covers all relevant process steps from raw material production to the HGNG-17 production.
For the implementation of the system models the “SimaPro7” LCA software has been used and the “Ecoindicator 99” methodology (implementing an “End-point level” Approach) and the CML 2001 method (implementing a “Mid-point level” Approach have been chosen (Goedkoop et al., 2000). The LCI of the CSP plant and the chemical plant (reformer unit) have been realized on the basis of the construction data directly provided by ENEA centre and Technip-KTI, respectively, while the LCAs of the conventional plants (reformer and cracker) for the hydrogen production have been performed by using data included in the Ecoinvent v.2.0 database. The data relate to international scenarios, which cover the entire industrialized world. Since co-products, such hydrogen and electricity, are generated by the hybrid plant, the allocation step is needed. In this study allocation procedures have been carried out via mass.
Finally, it is very important to draw some considerations about the reliability of LCA results reported in the next paragraphs. Indeed, the LCA results are affected by the several uncertainties associated with the inventory data used, therefore this can be considered only a preliminary study that needs of further development.

3. Results and Discussion

In Table 1 some preliminary aggregated data are reported relating to the construction of a CSP-Reformer hybrid plant for a continuous HCNG-17 production of 780 Nm^3, as well as the production of 132.5 Nm^3 of hydrogen and 3246 MWhe/year (Piemonte et al., 2010). The LCI data are directly provided by the Italian research centre ENEA and Technip-KTI. The LCA was performed considering the most important materials used for construction as well as the energy requirements for construction, while transport was implicitly included in energy consumption. The most important LCA results for the hybrid plant are summarized in Table 2. The results seem to be very interesting considering, for example, that the production of 1 Nm^3 of HCNG-17 by conventional processes, like steam reforming and cracking , lead to the production of 4.49 and 1.04 $kgCO2_{eq}$, respectively.

Table 1 Raw materials, energy demand and land use for the CSP+Reformer hybrid plant building

Raw material	**Amount**	**Raw material**	**Amount**
Concrete (kg)	334973	Mineral wool (kg)	6854
Steel (kg)	385600	Molybdenum (kg)	3289.6
Stainless steel (kg)	118934	Biomass (kg)	746048
Glass (kg)	62239	**Energy Demand**	
Plastics (polypropylene) (kg)	28000	Solar radiation (MJ/year)	70006154
Sodium nitrate (kg)	877241	Electricity (Italian mix) (MJ/year)	527427.0
Potassium nitrate (kg)	584827	**Land use**	
Zinc (kg)	116423	CSP plant (m^2)	36000
Nickel (kg)	28.2	Biomass growth (m^2)	750000

In the second part of the LCA study, hybrid plant environmental performance has been compared with respect to those of conventional plants, as reformer and cracker, characterized by the same Hythane productivity.

Figure 2 shows the comparison among the three plants assessed in this paper by using the Eco-indicator 99 methodology in terms of Damage Categories. The figure clearly highlights:

- the lower impact of the hybrid plant both for the damage category “Resources” and “Human Health”,
- the impact of the hybrid plant for the “Ecosystem Quality” substantially comparable with that of the conventional plants.

From an overall point of view the Figure 2 suggests that the hybrid plant is always preferable to the reformer plant (its impact is lower than that of the oil power plant for all the three damage categories). On the contrary the comparison with respect to the cracker plant must be further elaborated by means of the mixing triangle technique (Hofstetter et al., 2008).

Table 2 Main LCA's results for the CSP+Reformer hybrid plant in terms of specific emissions for 1 Nm^3 of HCNG-17 produced

Impact category	Value
Global warming 100a ($kgCO2_{eq}$)	0.405
Ozone layer depletion 25a ($kgCFC\text{-}11_{eq}$)	2.08E-8
Human toxicity 100a ($kg1,4\text{-}DB_{eq}$)	0.0726
Acidification ($kgSO2_{eq}$)	0.00197
Eutrophication ($kgPO4^{3-}{}_{eq}$)	0.000116
NOx ($kgNOx_{eq}$)	0.00106

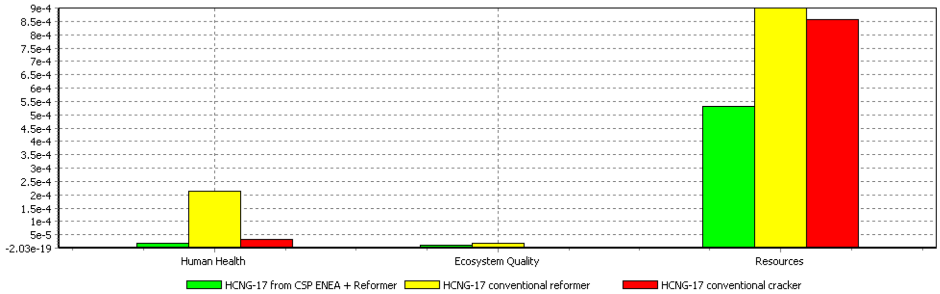

Figure 2: LCAs Comparison by means of the Eco-indicator 99 Methodology: damage oriented approach.

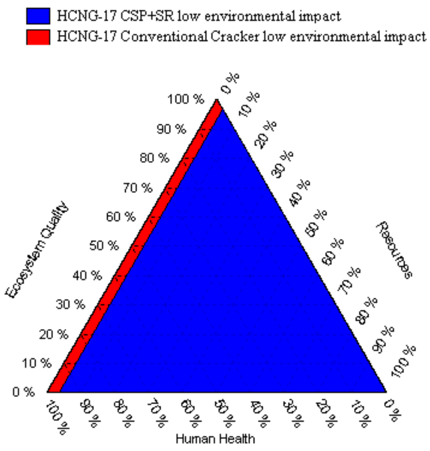

Figure 3: Comparison of the global impact of the CSP+SR plant vs. a Conventional Cracker plant by using the mixing triangle approach

Figure 3 shows that the cracker plant is preferable to the hybrid plant only for very high values of ecosystem quality or human health macro-categories, i.e. only if a very low importance to the resources depletion is assigned.

4. Conclusions

In this work the performance of a novel hybrid plant for the production of a mixture of methane and hydrogen (hythane) was assessed from an environmental point of view by using the LCA methodology. The hybrid plant was also compared to conventional plant for the production of hythane. Surely a deeper assessment has to be made, but results reported in this paper allow interesting considerations: by assigning reasonable values to the three damage categories used in the eco-indicator 99 methodology, the hybrid plant is always preferable with respect to conventional plants, confirming the high potentials of this innovative plant technology.

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