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# Optimal Design of Solar Assisted Hydrothermal Gasification for Microalgae to Synthetic Natural Gas Conversion

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Catalytic hydrothermal gasification is a promising technology which allows the conversion of wet biomass into methane rich syngas. It consists of three major steps, in which thermal energy has to be supplied at different temperature levels, leading to multiple products, such as clean water, nutrients/salts and methane rich syngas. Microalgae have an important potential as a new source of biomass, principally due to the fact that they can grow much faster than others biomass feedstock available in nature. Considering the energy balance of the algae cultivation step, the gasification process and the crude product upgrading step, part of the converted syngas has to be used to close the energy balance. In this context, solar heat can be considered as an alternative to replace the heat that has to be generated from product or crude product burning. This would lead to higher fuel production, higher carbon conversion efficiency and in general a better sustainable use of energy sources.
In this paper, the goal is to show the integration potential of solar thermal energy use in the catalytic hydrothermal gasification of microalgae. In order to maximize the fuel production, thermal energy requirements of the gasification and SNG upgrading process can be generated in concentrating solar systems, coupled with thermal energy storage. This allows to continuously provide heat for the process at different temperature levels. A superstructure of design models will permit the estimation of the optimal size and integration of the solar utility for different process configurations. The optimal design configurations are evaluated by solving a multi objective optimization problem which aims at the maximization of conversion efficiency and the minimization of operating and total production costs.

## 1. Introduction

Sustainable biomass to bio-synthetic natural gas conversion has been widely investigated in the last decades as a way to control carbon dioxide concentration in the atmosphere and to reduce fossil fuel exploitation. A multitude of feedstock, together with their conversion technologies have been proposed. Presently, due to competition between food and biofuel production in arable lands, the use of microalgae feedstock in non-arable lands seems to be a promising option (Brennan et al., 2010). One of the main challenges in microalgae conversion is the lower concentration at which the biomass is present in water. In this context, hydrothermal gasification would allow for the direct conversion of a partially dewatered microalgae feedstock, with solid content values ranging between 1 % and 20 %, this higher limit being imposed by stream pumping limitations. The integration of algae open cultivation systems and hydrothermal gasification has been recently analysed, including the Life Cycle Impact Assessment analysis (Mian and Ensinas, 2013).
Considering the energy balance of the system, it can be verified that thermal energy at high temperature has to be supplied to the process. A catalytic hydrothermal gasification process requires heat at a precise temperature interval, which depends on salt separation constraints, ranging from 380 °C and 550 °C. Some authors (Gassner et al. 2011) have investigated the energy conversion potential of wood feedstock, accounting for crude product burning and evaluating different ways to exploit the minimum amount of fuel to be used in order to close the energy balance of the gasification step. This is in general reducing the conversion potential in terms of synthetic natural gas production, and introduces an additional source of carbon dioxide emission in the conversion process.

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Solar thermal energy can be continuously provided to the system at temperature levels above 300 °C and up to 600 °C by using solar troughs, coupled with thermal energy storage. A study on the use of solar utility for glycerol hydrothermal gasification using molten salts as heat transfer fluid has been recently published (Azadi, 2012). It refers to hydrothermal gasification of glycerol, thus the salt separation thermal energy requirements are therefore not taken into account. In this paper the potential of using solar heat as an alternative source of thermal energy in the conversion of biomass to synthetic natural gas is investigated. The heat transfer fluid considered is hot air, which is produced by a parabolic trough receiver, the heat being stored in a packed bed of rocks thermal storage. This kind of technology has already been proved and it is considered as an attractive and cost efficient possibility (Zanganeh et al. 2012). The physical limitations of using air as heat transfer fluid are highlighted together with the energy integration analysis. Different plant configurations are evaluated in order to identify the best use of hot air. The analysis is done by applying pinch analysis and process integration techniques. A Mixed Integer Non Linear Programming (MINLP) problem is defined in order to optimally integrate the hydrothermal gasification and synthetic natural gas upgrading technology with the solar system. The results are presented for each considered plant design and pros and cons are highlighted.

## 2. Thermodynamic process modelling

Thermodynamic models are developed for each specific process by applying process synthesis techniques. Part of the conversion system is modelled using flow sheeting software which simultaneously solves the given system of equations. Other processes are modelled by following sequential approach.

### 2.1 Open system micro-algae cultivation

The cultivation of micro algae in open systems is a promising technology. It allows to valorise unusable lands in order to grow biomass with productivity rates which are in the worst case three times faster than that of biomass cultures such as mais, miscanto, wood, etc. (Williams et al., 2010). At present, several demonstration plants are present; the key energy aspects are mainly related to the electrical energy requirements for circulation and pumping streams in the pond. The system model is built using a sequential approach, accounting for location, radiation affecting the cultivation system and the temperature of the environment. A key aspect is the control of the pH index in the pond, which strongly affects growth rate. The pH in the pond can be controlled using carbon dioxide injection, which is then fixed in the biomass and partially lost. The model requires as inputs the yearly global horizontal radiation of the selected location, mean temperature of the pond, the pond depth, the algae final concentration just before the harvesting step, the low heating value of the dried algae biomass and its carbon elemental weight fraction. By sequentially solving the system of equations for mean stationary conditions during the year, the model calculates the specific biomass productivity P [$g/m^2$*d], the area of the required open pond in ha and the carbon dioxide fixation efficiency.

### 2.2 Hydrothermal gasification process and synthetic natural gas purification

The flow sheeting design model developed by Gassner et al. (2011) is used to identify the thermal and electric energy requirements of the hydrothermal gasification process. Concerning natural gas purification, water adsorption technology at a pressure of 70 bar is selected. This allows for lower methane losses with respect to membranes or flash separators (Gassner et al., 2011). The whole system is modelled by using the Belsim Vali flow sheeting software.

### 2.3 Concentrating solar thermal process and thermal storage

Concerning the solar technology, a different approach is used; the fact that the solar system is non-stationary is modelled in matlab by applying a sequential approach, and by considering an hourly steady state model. Direct Normal Irradiation, temperature of air and wind speed data for a given location are provided in the form of hourly data. These are recovered from weather data files given by U.S. Department of Renewable Energy. The model of the solar trough is built for a module of 1 MW thermal energy nominal power, and 1.34 MW thermal energy peak power. The power output is measured for a given receiver area of about 2000 $m^2$, as the enthalpy difference between the heat transfer fluid between the receiver output and inlet sections.

The heat transfer fluid has to be sent back to the receiver at a temperature lower than 250 °C, in order to reduce the heat losses along the return circuit, to reduce the blowers power consumption and allow for low diameters of pipes of the system. The model accounts for optical losses, thermal losses along the solar collector, and thermal losses along the hot air distribution circuit. All the contribution of losses previously mentioned are calculated using correlations, experimentally obtained from on-site measurements. The design variables which are accounted for in the definition of the losses are: the geographical location, $\theta_{skew}$

the skew angle (varying instantly), $I_{ins}$ the wall heat loss coefficient of the trough, ɣ the orientation of the trough with respect to the north-south axis. Location and skew angle affect optical losses; thermal losses are calculated with an experimentally validated function, which accounts for the skew angle, the design temperature of the hot air produced and the wall heat loss coefficient. The power output of the receiver is calculated as a function of Direct Normal Irradiation data, and optical and thermal efficiencies. A set of hourly power outputs is generated for each day of the year and is optimized by varying hot air temperature, orientation of the receiver, wall heat loss coefficient and return temperature of hot air.
Thermal storage systems are usually designed in order to supply thermal energy to a system continuously in the best Direct Normal Irradiation day. This is usually done in Concentrating Solar Power systems, but since one of the goals of the study is to check the feasibility of a 24 h solar driven hydrothermal gasification process, the possibility of a solar system design that allows operating the gasification plant continuously during a medium level DNI energy day is also considered. A representation of the complete flow-sheet and principle material streams is depicted in Figure 1.

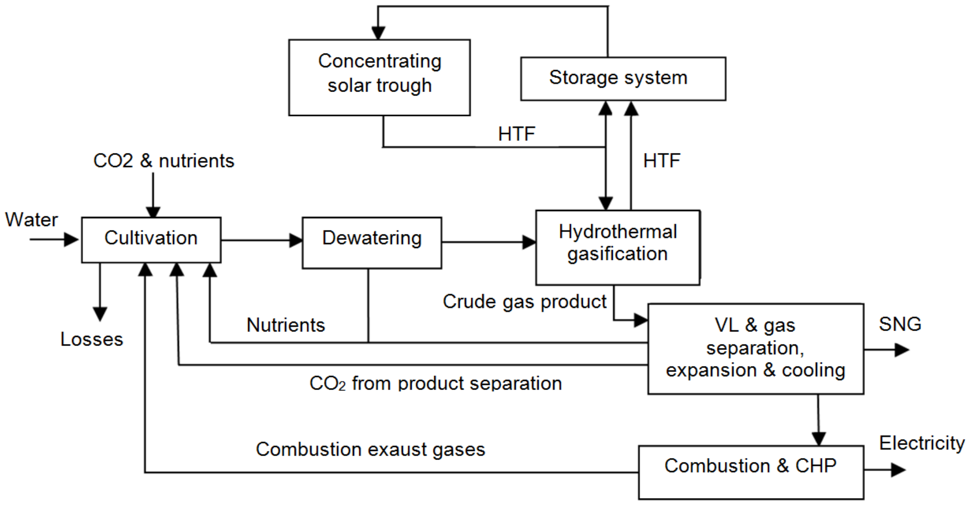


*Figure 1: System configuration*

**2.4 Utilities**

In order to perform energy integration, a set of thermodynamic models is built to model utility processes, applying flow sheeting approach. Two types of heat recovery Rankine cycles are modelled in matlab, with the possibility of using one or two pressure levels cycles, depending on waste heat availability. The design specifications are checked in a pre-compute model in order to prevent low quality steam at steam turbine output.
The possibility of burning waste streams leaving the syngas upgrading process is also accounted: for this purpose, according to previous analysis (Gassner et al. 2011), two main technologies are considered. A simple burning process is modelled as a first option, while a partial oxidation gas turbine is considered as a cogeneration option. Concerning the previously mentioned utilities, and accounting for the fact that these are coupled with mass flows leaving the gasification plant, partial loads are not accounted for since it is assumed that the gasification plant will operate continuously at the design point.

## 3. Energy Integration and optimization problem formulation

Pinch Analysis is used to optimally couple process requirements with hot and cold utilities. Energy integration of utilities and process hot/cold streams is performed by applying the approach of Maréchal et al. (1998). The energy integration is performed by considering a Mixed Integer Linear Programming (MILP) model, using the design day for the solar system, thus in conditions that will probably be reached only during some days in a year. All the thermal streams involved in the hydrothermal gasification, in syngas purification and storage output are accounted for in the heat cascade model. For each of the defined heat streams, a heat exchange minimum temperature difference is defined. This affects the heat cascade model resolution since it influences the Pinch Point of the process, and consequently acts also at the level of the utilities integration. The thermal solar utility is defined by considering three heat streams, at consecutive temperature levels from highest to lower temperature. A first MILP model is built to evaluate

the optimal temperature levels of the solar heat streams. This allows to optimally couple heat streams of the process, to reduce exergy losses, and to reduce stratification at the level of storage by considering recirculation (Crandall et al., 2004). on the results obtained and some technological constraints, a second model is built to evaluate the energetic performances of the system and its costs, considering the actual level of solar technology. The hydrothermal gasification process needs heat at a temperature interval between 600 °C and 380 °C, and slightly varies with the maximum temperature reached in the salt separation. Due to this last aspect, and also to the fact that it is mandatory to cool down hot air to at least to 250 °C, the use of this additional amount of heat has to be evaluated. At this point heat recovery steam cycles can represent a potential solution; the second MILP model is built to analyse this option.
A two-step approach is used to systematically perform operating and investment cost minimization under the constraints of the heat integration. The optimization tool consists in a two-steps approach, performing a master and a slave optimization. Operating costs are minimized while solving heat cascades in a slave optimization problem, while the nonlinear objective functions are accounted for in a master loop which uses evolutionary algorithm to define the Pareto frontier.

## 4. Results

The result of a first analysis of temperature levels of the solar utility is depicted in Figure 2.A The integration of the solar utility avoids the burning of synthetic natural gas products when the solar system is at the design point. Figure 2.B shows the temperature-enthalpy profile of utilities when the crude product is burned in a post oxidation gas turbine. It can be seen that solar heat at a lower temperature level allows not only increasing the production of natural gas, but also highly reduces the exergy losses.

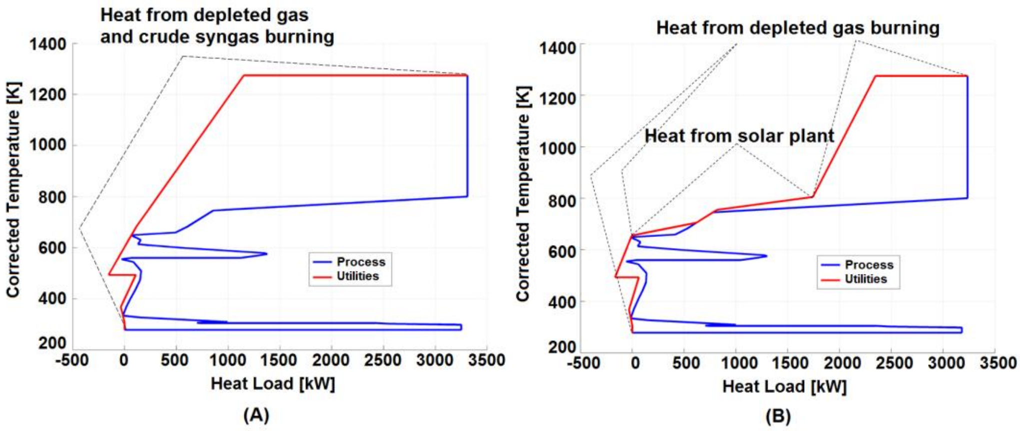


*Figure 2: Heat load distribution of utilities and process streams without (A) and with (B) solar utility, in corrected temperature – heat load diagram*

As discussed in the previous paragraph, the lower temperature level of the solar utility which is selected by the optimizer is in fact far from the technological limit related to the use of hot air as heat transfer fluid. Considering the 20 MW dry biomass input at the gasification step, the presented solution allows to increase the synthetic natural gas production, in design conditions, from 12 $MW_{SNG}$ to 14 $MW_{SNG}$. On the other hand, the use of solar utility decreases the net electricity balance, since it requires significant electricity to drive the air blowers. Also, the production accounted for while burning part of the crude product disappears from the electricity balance. The net electricity balance which is slightly negative in normal conditions is thus decreased, though globally the overall energy efficiency of the plant increases from 65 % to 75 %.
These values can be reached as soon as the heat transfer fluid can be recirculated back to the solar system – high temperature storage. The key aspect is related to the higher pinch point of the system, which is at 650 K in the corrected temperature scale. The pinch point is located in the system at the salt separator and in addition, all the heat that it is required from the process above this pinch point is heat required in the salt separation unit. Hot air is in this case not the best heat transfer fluid, and for this reason the system including a heat recovery steam generator is studied as second option. From the first analysis, and considering the wide range of input temperature that the trough can handle, it is clear that the temperature at the trough input is defining the size of the solar system, and as a consequence affects the overall investment costs.

A second configuration is defined to include the constraint of hot air returning at a temperature of 120 °C to the solar isle, and to account for electricity production using a heat recovery steam generator and Rankine cycle. The two pressure levels, together with the temperature at the turbine inlet, are set as decision variables of the master optimization. In addition, a controller is set before each simulation to adjust if necessary the superheating temperature in order to prevent low quality of steam at the turbine output. The system boundaries are thus changed by considering a double pressure Rankine cycle, which allows for electricity production. The heat integration model is also modified, the lower temperature level of the solar utility stream is fixed at 120 °C, in order to maximize the power recovery, and the streams related to steam production at different pressure levels are introduced in the heat cascade problem. The MINLP is solved considering as objectives; the minimization of operating costs at the level of the slave optimization and the maximization of syngas production and minimization of total costs at the level of the master optimization. The result of the energy integration it is depicted in Figure 3, where the corrected temperature – enthalpy profile of the utilities and the process and the Rankine cycles are depicted.

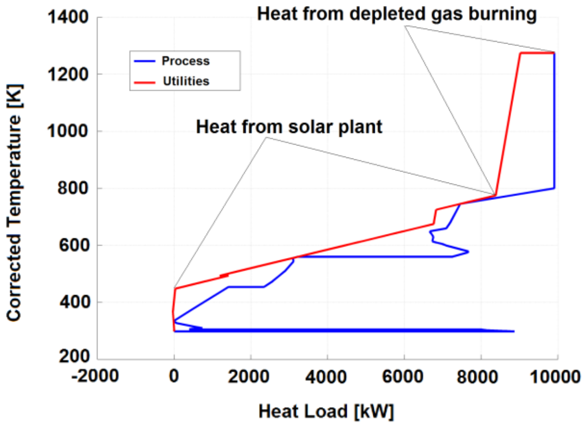


*Figure 3: Heat load distribution of utilities and process streams with use of a heat recovery double pressure level Rankine cycle and hot air coming from a solar trough-receiver, output at 200 °C*

The size of the solar system, this has considerably increased with respect to the first analysis. For a 20 MW dry biomass input gasification it is required to install almost 12 MW solar trough system, which is much higher than what is required for the gasification. As result of the optimization the pressure levels of the steam cycles which are selected are, respectively, 10 bar at low pressure and 70 bar for medium pressure. The net electricity balance is widely positive and 1 MW of electricity is produced for plant design operating conditions. The efficiency of this conversion is lowered with respect to the previous analysed model, due to low mean temperature of the heat recovery thermodynamic cycle. The energy efficiency is calculated at 48 %, while the exergy efficiency reaches 43 %.

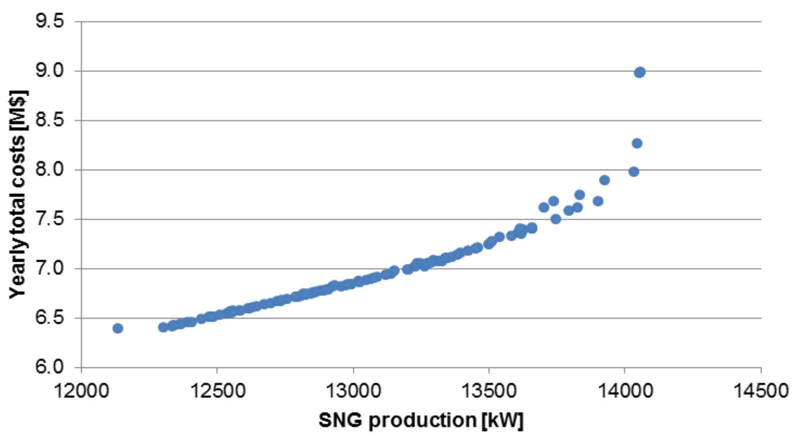


*Figure 4: Pareto frontier of optimal solutions*

## 5. Conclusions

The integration potential of a concentrating solar system technology with hydrothermal gasification of micro-algae has been presented in this paper. Thermodynamic models of micro-algae cultivation systems and hydrothermal gasification have been implemented considering literature values and existing analyses. A thermodynamic model of a parabolic solar trough producing hot air at temperature levels of up to 650°C has been developed, and validated according to an existing system which is actually produced by Airlight Energy SA. The key point for integration purposes is related to the heat demand of the gasification plant, the temperature level characterizing the Pinch Point of the process at high temperature, activated by the salt separator design. The constraints related to hot air circulation in the circuit oblige the cooling down of part of the produced heat with the solar system. The use of liquid heat transfer fluids compatible with high temperature pumping would probably allow the system to reach better performances with the considered conversion system, which are at best equal to results shown in the first case study. An additional optimization problem is required in order to evaluate the optimal operating conditions of the solar system for partial loads.

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