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Water–energy nexus in biofuels production and renewable based power

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ABSTRACT

In this paper, the water–energy nexus for renewable based processes is evaluated. Process synthesis and integration techniques are used to synthesize the processes and integrate the energy and water, optimizing the consumption of both natural resources. In the analysis of water consumption, it was found that cooling needs and water using technologies are major drivers. Currently, contaminated water is treated for further use. Therefore, the more the energy is integrated, the lower the cooling needs are reducing the water consumed. FT-fuels was identified as the most efficient process in terms of water–energy consumption, with other options being second generation bioethanol via gasification and catalytic synthesis, biodiesel production from cooking oil, and the integrated process that produces biodiesel and glycerol ethers, as long as the rainfall water is not included in the analysis. Otherwise, solar based fuels are more efficient.

Keywords: Energy; Alternative fuels; Water; Water–energy nexus

1. Introduction

Water and energy are two interrelated natural resources (Azapagic and Perdan, 2014). Typically, not much attention has been paid to the consumption of water due to its low price and relative availability. However, generally the production of energy, requires a considerable amount of water. For instance, the production of power in thermal plants requires around 1.8 L/kWh (Torcellini et al., 2003). In this particular case the water consumed is mostly the one lost by evaporation in the cooling tower. In the production of petrol or diesel, there is a certain amount of water injected to extract the crude, around 2.5 L/L (Wu et al., 2009). These two examples show that, although there is a strong link between both resources, each product and process determines the actual value, and most importantly, where it is possible to implement further water and energy saving technologies. The renewable sources of energy such as solar, wind, biomass can be processed in a number of ways to obtain power and fuels. Furthermore, the production of biomass itself requires special consideration. If the biomass is not native to a certain region and there is not enough natural irrigation, there is a large amount of water needed to grow it (Wu et al., 2009). For instance, sugar cane in Brazil grows with no artificial irrigation, whereas in many cases there is need for a supply of water to produce the biomass.

While on the one hand, energy production (or fuels) requires energy, on the other hand, energy is required to treat and transport water. The water used in any process comes out with increased levels of contaminants. This water needs to be reintegrated in the system, and for that the levels of contaminants must be reduced to those established by environmental regulations.

In this work, we analyze different primary renewable sources of energy such as biomass, solar and wind and a number of processes that transform them into power and a

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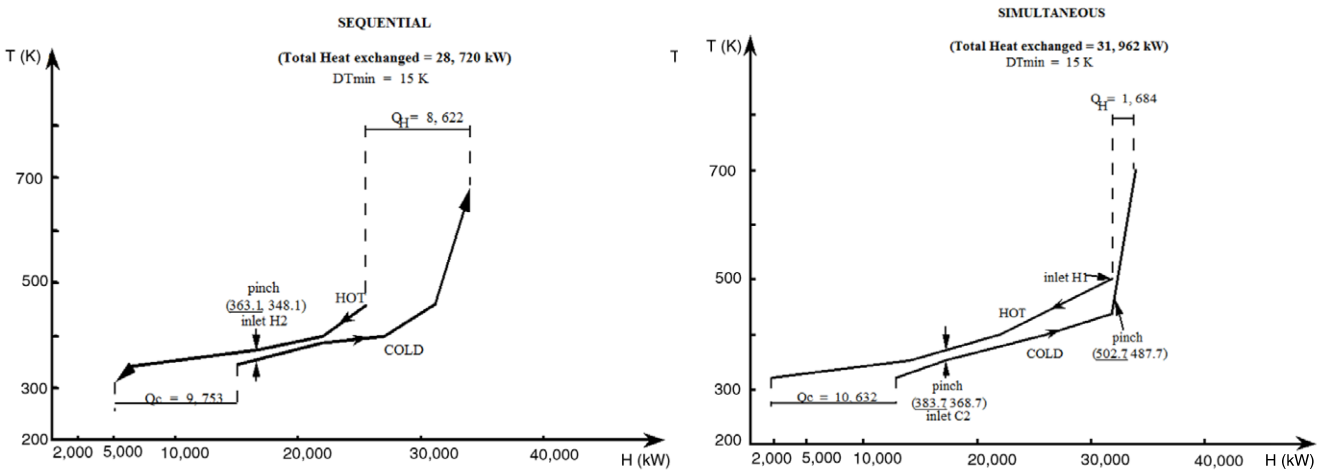

(a) Sequential approach. **(b) Simultaneous approach.**

Fig. 1 – Comparison of the use of simultaneous optimization and heat integration. With Permission (Duran and Grossmann, 1986).

number of common fuels, not restricted to bioethanol and biodiesel, discussing the sinks and sources of water and energy for each case. Based on previous work on process design and integration for computing energy and water consumption, we report the amount of water used per MJ of energy produced in order to gain some insights into the water–energy nexus for the processes and their water efficiency.

2. Methodology

The optimization of water and energy is a well studied area within the process engineering community. The seminal papers on energy integration for process design deal with the development of the pinch technology (Linnhoff and Hindmarsh, 1983), the use of mathematical optimization techniques for the simultaneous optimization and heat integration (Duran and Grossmann, 1986), or the design of heat exchanger networks (Yee and Grossmann, 1990). With regards to water consumption, major works include Takama et al.'s paper in (1980) formulating the first water network, to the heuristics presented by Wang and Smith (1994) developing the water pinch, and the novel formulations and solution procedures for the water network as in Galan and Grossmann (1998), Karuppiah and Grossmann (2006) and Ahmetovic and Grossmann (2011). Traditionally, previous studies have considered each resource, water and energy, independently. One reason for this is that the problems by themselves are quite difficult. Water networks (WN) and heat exchanger networks (HEN) lead to non-convex mixed-integer nonlinear programming problems for which global optimal solutions are hard to obtain. Furthermore, large mixed-integer nonlinear programming models arise when a number of alternative technologies are considered for the processing of a certain raw material into a desired product (i.e. Martín et al., 2011).

The optimal design of renewable based fuels and power production can be carried out using a sequential approach for optimizing first the topology and energy, and in a second step, optimizing the water consumption (Grossmann and Martín, 2010). In the first stage the process is designed, including simultaneous optimization and heat integration in those cases where models for the reactor conversions are available. Once the topology of the process is fixed and the optimal operating conditions are determined, models such as the one by Yee and Grossmann (1990) are used to develop a heat exchanger network, minimizing simultaneously the utilities and the investment cost. Finally, water is integrated by designing a water network by using the model developed by Ahmetovic and Grossmann (2011). We need to bear in mind that process decisions and flowsheet topology could incorporate water optimization within the first stage, however, the mathematical complexity increases. Alternatively, Yang and Grossmann (2013) formulated an LP targeting approach to simultaneously optimize the process and the consumption of water and energy, limiting the mathematical complexity added to the problem. The use of this formulation provides either exact results or tight upper bounds (Yang and Grossmann, 2013).

2.1. *Process synthesis and energy optimization*

A superstructure optimization approach is a powerful tool to evaluate a large number of alternatives in a systematic way. First, each of the units in the superstructure must be modeled. There is a trade-off between accuracy and simplicity. For optimization purposes, the size of the problem when the complete superstructure is formulated suggests the use of simple models based on mass and energy balances, rules of thumb, thermodynamic principles (kinetics and species equilibrium) and experimental results and trends (Martín and Grossmann, 2012a).

Once the units are modeled, the superstructure optimization model is put together. Furthermore, we can incorporate Duran and Grossmann's (1986) formulation for simultaneous optimization and heat integration. The formulation is based on a search of the pinch point among candidates from each of the streams involved in the process. Compared to the sequential approach, the overall conversion and the profit can increase if simultaneous integration and heat integration are considered together with process design. In terms of heat integration, Fig. 1 shows the comparison between the composite curves in using a sequential approach (a), and the simultaneous approach (b) by the formulation. As can be seen, a significant reduction in the energy required for the process is achieved.

At this point, the optimal topology and operating conditions result from solving a large MINLP. The second step is to use the Yee and Grossmann (1990) model for the streams