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Optimal integration of renewable based processes for fuels and power production: Spain case study

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HIGHLIGHTS

- A network integrating renewables sources for fuel and power production is proposed.
- Wind, solar, waste, biomass, CO_2 and water are the resources.
- Intermediates required such as methanol or thermal energy are internally produced.
- The network allows selecting best set of integrated technologies and resources.
- Entire countries and uncertainty effect can be evaluated with this framework.

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ABSTRACT

In this work we propose a data independent framework for the optimal integration of renewable sources of energy to produce fuels and power. A network is formulated using surrogate models for various technologies that use solar energy (photovoltaic, concentrated solar power or algae to produce oil), wind, biomass (to obtain ethanol, methanol, FT-liquids and thermal energy), hydroelectric, and waste (to produce power plant via biogas production). The optimization model is formulated as a mixed-integer linear programming model that evaluates the use of renewable resources and technologies and their integration to meet power and fuels demand; sustainability and CO_2 emissions are also considered. The network can be applied to evaluate process integration at different scales, county to country level, including uncertainty availability of resources. Spain and particular regions are used as a case study. The framework suggests that larger integration uses the resources more efficiently, while considering uncertainty in resource availability shows larger cost to ensure meeting the demand. For the particular case considered, hydropower is widely used while biofuels are produced close to large populated regions when larger areas are evaluated; otherwise a more distributed solution is proposed. Reaching large fuel substitution is difficult at current biomass yields and technology state of development.

1. Introduction

Concern on global warming, the increasing demand for energy and the more restrictive directives on greenhouse gases (GHG) emissions have paved the way for a larger share of renewables in the energy mix. Among them, hydropower, wind, solar and biomass are the most commonly used [1]. While biomass is a raw material than can be stored for a certain period of time, and hydropower can be regulated [2–4], solar and wind energy are more difficult to manage [5–6]. Currently battery systems do not have the capacity to store large amounts of power [7–8]. Therefore, to meet a certain demand of power and fuels, and mitigate the effect of the availability of renewable sources, several technical alternatives are available including thermal storage [9–10], chemicals production, i.e. hydrogen [11–12] or methane [13], or hydro-storage [2–4]. Over the last years, process integration involving various renewable resources has been considered for a more efficient use of them, managing their variability and availability [14]. First and second generation bioethanol production processes were integrated to use the excess of energy when processing lignocellulosic biomass for ethanol dehydration [15]. Not only biomass types, but different energy sources have also been integrated. For instance, it is possible to design a facility that combines concentrated solar power and biomass for a constant power production capacity over time [16]. Martín and Davis [13] evaluated the integration of solar and wind power for the

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Nomenclature

B CO_2 mitigated due to the production of a byproduct (kg CO_2/yr)
$Biodiesel_{prod}(t)$ biodiesel produced in period in a particular zone (kg/s)
$Biomass\_use_P$ consumption of biomass in period by process p (kg/s)
$Biogasoline_{prod}(t,p)$ renewable substitutes of gasoline in process p (kg/s)
C_{Annual} annual coefficient
C_{CT} carbon tax (€/kg)
$CH4_P(t)$ methane produced in period t (kg/s)
$CO_{2fossil}(t)$ flow of CO_2 from fossil fuels used (kg/s)
CO_{2P} (t) flow of CO_2 used or produced in process p (kg/s)
$Cost_E$ fixed parameter of cost for the piecewise linear approximation (MM€ or MM€/y)
$Cost_{Invest}$ investment cost (MM€)
$Cost_{Prod}$ production costs (MM€/s)
DemandP power demand (kW)
E CO_2 generated or mitigated due to energy consumption/production (kg CO_2/yr)
F CO_2 generated due to fertilizers production (kg CO_2/yr)
$Feed_i$ Feed flow of component i to a process
F&F Burden due to the impact of a raw material in the food industry $/yr
I investment (€)
In (p,t) inlet flow to process p in period t
JS impact of the investment in the jobs generated (€/yr)
K_i operating parameter for main operation of a process p
M CO_2 mitigation by substitution of fossil resources by renewable ones kg CO_2/yr)
P production costs (€/yr)
$Power_{gen}(t)$ power generated in the network in period t (kW)
$Power_{use}(t)$ power used by the network in period t (kW)
PowerP(t, p) power produced or consumed by process p in period t (kW)
Production(Process,Out) Flowrate of process P exit out
Biomass_useX(t) Flowrate of biomass in process X in period t
SyngasX(Process,Out) Flowrate of process P exit out
$Prod_i$ Product i from process
$Q_P(t)$ cooling required by process p in period t (kW)
Q_i Operating parameter for feed i of process
RM CO_2 produced in the generation of a Secondary Raw material (kg CO_2/yr)
t period (month)
ThermalE(p, t) thermal energy produced or consumed in period t by process p (kW)
W CO_2 generated due to water consumption (kg CO_2/yr)
VarD = $Design_{Variable}$ design variable for a particular process
Yproc(process) binary variable for the existence of a process p
Y_P binary variable for the piecewise linear approximation
Z objective function (€/s)
θ stochastic parameter
$\lambda_{Process}$ variable for piecewise linear approximation

production of methane, synthetic natural gas. Prasad et al. [17] evaluated the integration of solar and wind energy for power production to mitigate the lack any of the sources. Martín and Grossmann [18] integrated solar, wind and biomass to capture CO_2, mitigating GHG emissions, to produce biodiesel with no need for fossil based intermediates. Hybrid fossil-renewable systems are also presented in the recent literature [19]. The design of most of the facilities involving renewables is subjected to the variability in the energy sources and that of the electricity price [5,18]. This variability affects the use of the units of the process, not only wind turbines and solar panels, but also the number of electrolyzers in operation and process units. Some units may remain idle or partially idle for certain periods of time representing an investment in units that are not used to their full capacity [18]. Resource variability determines the investment in expensive units. Therefore, the design problem involves multiperiod optimization under uncertainty. This kind of problems has been addressed before in the literature [20]. Grossmann and Sargent [21] included the uncertainty in the information within process design. Later, Halemane and Grossmann [22] described the problem of flexible process design. Both concepts have regained attention with the inclusion of renewables in the energy mix. In the integration of methanol via hydrolytic hydrogen and algae based oil [18], the problem is formulated in such a way that it exploits the operation of the plant to reduce the problem size. Martín [23] presented a methodology to address the design and monthly operation of plants using renewable sources for the production of methanol from CO_2 hydrogenation. Surrogate models are developed, not only for the process units, but also for the cost of the process sections so as to be able to include uncertainty in solar and wind into the design decisions. Recent examples show the integration of hydro and photovoltaic power [24].

However, large scale demand such as at regional or country level requires the integration of resources at a larger scale, a problem that represents a technical challenge [25]. Some studies [14,26] present overviews regarding integration possibilities as a perspective for the combination of different sources of energy. In order to help make those decisions, process system engineering has the tools to compare sources, technologies and locations in search of the optimal use of natural resources for renewable power and fuels production. Large scale integration of resources to control production capacity is challenging due to the problem size and its mathematical complexity, together with the fact that renewables feature seasonal and daily variation. Most of the studies either focus on biofuels supply chain design for different regions such as Europe [27], the US [28] or Canada [29], or electric power supply and grid operation based on the unit commitment problem [30], considering market prices [31] even including stochastic behavior of the variables [32], in particular applied to small regions [33]. In the case of the power sector, heat is also typically included in the analysis [34]. However, electric power is most of the times produced using a fuel that may be synthesized such as methane or Fischer Tropsch liquids. Therefore, both supply chains are linked and must be addressed simultaneously. So far both have been designed independently due to the fact that they are areas that are studied by different communities and most times focus on one resource only, ethanol, diesel or power [27–34]. Furthermore, individual processes were considered to be installed at each locations.

Thus, in this work we extend the analysis of the generation of biofuels and power using renewable sources by integrating the two supply chains that traditionally have been developed as independent entities by designing an integrated network of processes. Actually, the production of chemicals, fuels and power are linked by the common use of raw materials and resources, chemicals and fuels require thermal and electrical energy while the production of the later shares the same renewable raw materials. Furthermore, to instantly meet power demand, the possibility of storing power in the form of chemicals provides flexibility to the network. In this sense, the integration is more robust since chemicals and hydropower facilities can be used to store energy. A mathematical framework is developed using surrogate models for a large number of technologies that use most renewable based sources of energy such as solar, wind and biomass and transform them into fuels and power. The models are obtained from optimized process flowsheets and detailed economic evaluation considering not complete production processes but sections of actual processes to provide flexibility in the