Anton A. Kiss, Edwin Zondervan, Richard Lakerveld, Leyla Özkan (Eds.)
Proceedings of the 29th European Symposium on Computer Aided Process Engineering
June 16th to 19th, 2019, Eindhoven, The Netherlands.

Optimal design and planning multi resource-based energy integration in process industries

Shabnam Morakabatchiankar[a], Fernando D. Mele[b], Moisés Graells[a], Antonio Espuña[a]

[a]*Chemical Engineering Department, Universitat Politècnica de Catalunya, EEBE. Av. Eduard Maristany, 10-14, Edifici I, Planta 6, 08019 Barcelona, Spain*
[b]*Departamento de Ingeniería de Procesos, FACET, Universidad Nacional de Tucumán (UNT),Avenida Independencia 1800, S. M. de Tucumán T4002BLR, Argentina*
shabnam.morakabatchiankar@upc.edu

Abstract

Recently, process industries have experienced a significant pressure to shift from centralized energy supplying systems to the in-situ exploitation of renewable resources. Special attention has been paid to multi resource-based energy systems, a particular case of distributed generation where processing nodes include energy generation and can operate either grid-connected or isolated. This work proposes a general model to determine the optimal retrofitting of a supply chain integrating renewable energy sources under uncertain conditions and to analyze the effect of different planning horizons in the solution. The proposed mixed integer linear programming (MILP) formulation allows determining the best combination of available technologies that satisfies the internal energy demand of a given set of scenarios while addressing total expected cost and expected environmental impact minimization. The potential of the approach is illustrated through a case study from the sugar cane industry proposed by Mele et al. (2011).

Keywords: Multi resource-based energy, Optimization under uncertainty, renewable energies, closed-loop energy integration

1 Introduction

Growing energy demand about 60% over the last 30 years and increased industrial electricity and gas prices more than double in comparison with 20 years ago ((Zukunft, 2014) force industries to plan their eventual transition to a new energy system that will be largely based on Renewable Energy Sources (RES). This is one of the greatest challenges of our time. Over the latest years, process integration involving different renewable resources for their more efficient use, managing and controlling their uncertain availability, has been considered. Therefore, several alternative approaches are available to satisfy process energy demand and exploit the availability of renewable sources. In this line, a number of studies have been focused on single renewable sources such as first and second generation bioethanol production processes, which were integrated to use the excess of energy when processing lignocellulosic biomass for ethanol dehydration (Čuček et al. 2011; Mele et al. 2011), and cogeneration exploitation (Morakabatchiankar, Hjaila, Mele, Graells, & Espuña, 2018). Different energy sources have also been integrated with biomass types (Martín & Grossmann, 2017; Prasad et al. 2017; Vidal & Martín, 2015). Recently, Martín et al. (2018) proposed an integrated renewable energy resource network to produce biofuels and generate power combining two supply chains that traditionally are developed as independent entities. However, the satisfaction of large scale demands of multiple resources, such the one that should be faced at regional or country level, requires the integration of resources at a larger scale and needs more flexibility in terms of resources configuration. Hence, this work is focused on the development of a general optimization model for the retrofitting of sustainable process systems integrated with multi-energy generation system. The model is applicable to different ranges and scales while considering energy demand uncertainty to optimize the decisions of country-size SCs in the presence of conflicting objectives at different time spans.

2 Problem statement

According to the objective previously outlined, the proposed model determines a generic multi resource-based integration supply chain network as illustrated in Fig. 1. It is aimed to propose configurations associated with structural decisions that can be considered more sustainable. These decisions include the type, number, location and capacity of the energy generation units and production process plants (including the technologies selected in each of them); their capacity expansion policy and the transportation links between the energy-material SCs entities. The operational decisions are the energy generation level, the production rate at the plants in each time period, the flows of materials and energy between plants, warehouses and product markets, and the sales of final products and excess energy. Then, the SC configurations obtained by means of stochastic mathematical programming at different planning horizons can be compared. Additionally, this generic model determines the power to be installed at each internal or external resource and also the capacity of the required storage systems.

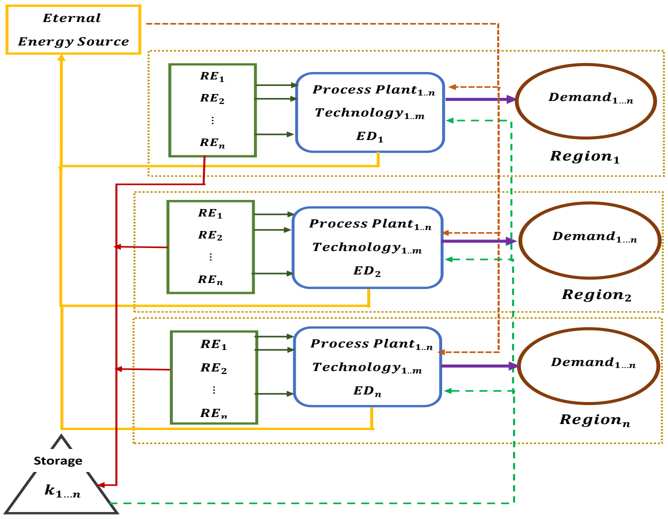

Fig 1. Multi resource-based Energy Integration SC

3 Multi-Objective stochastic Model

In this work, a scenario-based stochastic MILP formulation, considering a given distribution probability along the whole time horizon, based on the models introduced by Mele et al., (2011) (production process part) and Alabert et al., (2016) (multi resource energy integrated part) is proposed. Sizing is constrained to accomplish all scenarios, and operation variables are calculated according to each scenario. The number of necessary scenarios will be set in accordance with the characteristics of the case study to deal with. The model equations are classified as i) production process mass balances and capacity constraints; ii) energy generation mass/energy balances and capacity constraints; iii) energy storage management iv) External resources management; and v) objective function. The result of the model provides a set of Pareto solutions to be used by the decision maker in order to take the optimum tactical/strategical decision.

3.1 Energy generation

The balance representing the need to meet the (uncertain) energy demand during a certain period is shown in equation 1:

$$\sum_{ei} EnIJ_{ei,g,t,sc} + \sum_{ex} EnXJ_{ex,g,t,sc} + \sum_{k} EnKJ_{k,g,t,sc} = ED_{g,t,sc} \qquad \forall g,t,sc \qquad (1)$$

where $EnIJ_{ei,g,t,sc}$ is the energy flux between source ei and region g at time period t for scenario sc; $EnXJ_{ex,g,t,sc}$ is the energy flux between the external source x and region g at time period t for scenario sc; $EnKJ_{k,g,t,sc}$ is the energy flux between storage k and region g and $ED_{g,t,sc}$ is total energy demand in region g at time period t.

For the management of the own energy sources, the energy balances in equations (2) and (6) consider that all the generated energy has to be consumed or sold. The variable $EnEx_{ei,t,sc}$ represents the eventual excess of energy, and *SL* represents the slot length.

$$EnIG_{ei,g,t,sc} = PwIG_{ei,g,t,sc} \times SL \qquad \forall ei,g,t,sc \qquad (2)$$

$$PwI_{ei} \le PwIMax_{ei} \qquad \forall ei,g \qquad (3)$$

$$TotalEnIG_{t,sc} \ge TotalED_{g,t,sc} \qquad \forall g,t,sc \qquad (4)$$

$$\sum_{g} EnIJ_{ei,g,t,sc} + \sum_{ex}\sum_{g} EnIX_{ei,g,ex,t,sc} + \sum_{k}\sum_{g} EnIK_{ei,k,g,t,sc} + EnEx_{ei,t,sc} = \sum_{g} EnIG_{ei,g,t,sc} \qquad \forall ei,t,sc \qquad (5)$$

$$PwEx_{ei,t,sc} = EnEx_{ei,t,sc} / SL \qquad \forall ei,t,sc \qquad (6)$$

Equations (7-9) allow the management of external energy sources; they are similar to (4-5), but adding the possibility to sell energy. In these equations, $EnXP_{ex,t,sc}$ denotes energy purchase, whereas $EnXS_{ex,t,sc}$ represents the energy sales. Energy to be sold can only come from stand-alone generation, and it is considered that extra energy can be accumulated in storage elements.

$$PwX_{ex} \le PwXMax_{ex} \qquad \forall ex \qquad (7)$$

$$EnXP_{ex,t,sc} = \sum_{g} EnXJ_{ex,g,t,sc} + \sum_{k} EnXK_{ex,k,t,sc} \qquad \forall ex,t,sc \qquad (8)$$

$$EnXS_{ex,t,sc} = \sum_{ei}\sum_{g} EnIX_{ei,g,ex,t,sc} \qquad \forall ex,t,sc \qquad (9)$$

Storage units are modelled through equations (10) to (12), which introduce the charge and discharge limits.

$$EnK_{k} \le EnKMax_{k} \qquad \forall k \qquad (10)$$

$$EnKCh_{k,t,sc} = \left[\sum_{ei}\sum_{g} EnIK_{ei,g,k,t,sc} + \sum_{ex} EnXK_{ex,k,t,sc} \right] \times EfCh_{k} \qquad \forall\, k,t,sc \qquad (11)$$

$$EnKDh_{k,t,sc} = \sum_{g} EnKJ_{k,g,t,sc} \times 1 / EfDh_{k} \qquad \forall\, k,t,sc \qquad (12)$$

3.2 Costs equations

The objective function considers the installation and operational costs of the facilities along with the planning horizon (eq. (13) and (14)), also considering the environmental impact costs for installation and operation Eq. (15) and (16).

$$CIns = \sum_{ei}\sum_{g} \Pr PwI_{ei} \times PwI_{ei,g} + \sum_{k} \Pr EnK_{k} \times EnK_{k} \qquad (13)$$

$$\begin{aligned} COP_{t,sc} = {} & HL / PL\Big(\sum_{ei}\sum_{g} \Pr EnI_{ei} \times EnIG_{ei,g,t,sc}\Big) + \\ & \sum_{ex} (\Pr EnP_{ex} \times EnXP_{ex,t,sc} - \Pr EnS_{ex} \times EnXS_{ex,t,sc}) + \\ & \sum_{ex} (\Pr EnCh_{k} \times EnKCh_{k,t,sc} + \Pr EnDh_{k} \times EnKDh_{k,t,sc}) \end{aligned} \qquad \forall\, t,sc \qquad (14)$$

$$GHGIns = \sum_{ei}\sum_{g} GHGPwI_{ei} \times PwI_{ei,g} + \sum_{k} GHGEnK_{k} \times EnK_{k} \qquad (15)$$

$$GHCOP = \begin{aligned} & (HL / PL)\sum_{ei}\sum_{g} GHGEnI_{ei} \times EnIG_{ei,g,t,sc} \\ & + \sum_{ex} GHGEnX_{ex} \times EnXP_{ex,t,sc} \\ & + \sum_{k} GHGEnCh_{k} \times EnKCh_{k,t,sc} \\ & + GHGEnDh_{k} \times EnKDh_{k,t,sc} \end{aligned} \qquad \forall\, t,sc \qquad (16)$$

3.3 Objective functions

The whole SC system must attain two targets: an economic objective, represented by the NPV, and an environmental objective quantified by the global warming potential (GWP). Different NPV values are obtained for each scenario under study, so an expected value ($E[NPV]$) of the resulting NPV distribution can be computed by considering the estimated probability for each scenario:

$$E[NPV] = \sum_{sc} Prob_{sc} \times NPV_{sc} \qquad (17)$$

The resulting objective functions are finally expressed as follows:

$$Min\{-E\left[NPV\right]; E[GWP]\} \qquad (18)$$

S.t. constraints 1-17 and the constraints proposed by Alabert et al., 2016; Mele et al., 2011

The solution of this problem consists of a set of Pareto optimal SC configurations, which can be by applying the ε -constraint method.

4 Case Study

The first example introduced by Mele et al. (2011), which addresses the optimal retrofit of an existing sugar cane industry established in Argentina, is revisited herein: 5 different technologies are available to manufacture 2 main products: ethanol and sugars. Nominal capacity of the sugar mill and the distillery plants are 350 and 300 thousand tons per year. The time horizon is divided into a set of time periods, and the specific geographic area is divided into a set of regions where the facilities of the SC can be located. Each region has an associated supply capacity (sugar cane crop) at every time interval. Waste (bagasse) is supposed to be sent to cogeneration units to produce electricity as added-value product. Energy demand uncertainty is represented by 3 scenarios. Following Illukpitiya et al. (2013) assumptions, the estimated total electricity requirement for internal use in the processing plants is 0.0441 kWh per kg of cane. It is also assumed that the nominal capacity of the power plant is 8.33 MW and the power generation is available on a continuous basis for at least 7800 h annually. The electricity market price and the operational cost of electricity generation are 0.15USD/kWh and 0.08USD/kWh respectively.

5 Results

Figure 2 shows the Pareto curve obtained using the stochastic approach under several CO_2 emission levels and depicts a compromise between Expected Net Present Value and Expected Global Warming Potential. Each solution represents a specific design configuration of whole energy/material supply chain system. The results show that by increasing planning horizon length NPV value increases so it is also interesting to point out that, for the same cogeneration capacities of renewable resources, NPV increases up to 50% in longer planning horizons but tends to be constant for horizons longer than 10 years (Fig. 3). It is observed that the solutions allow operating at most for satisfying energy demand so that it involves more resources for generating renewable energies. As it is also shown in Fig. 4, a significant part of the expected electricity demand should be supplied by wind turbines.

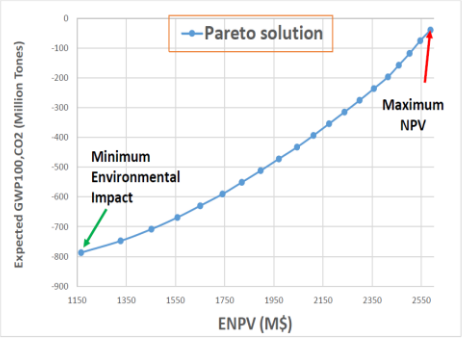

Fig. 2 Pareto set of solutions EGWP100 vs ENPV

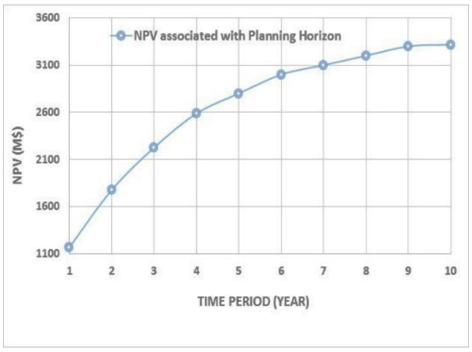

Fig. 3 NPV variation in Planning Horizons

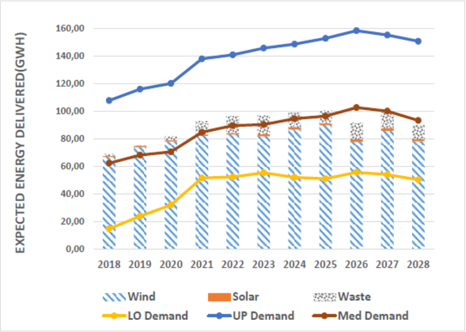

Fig. 4 Energy generation per Resource

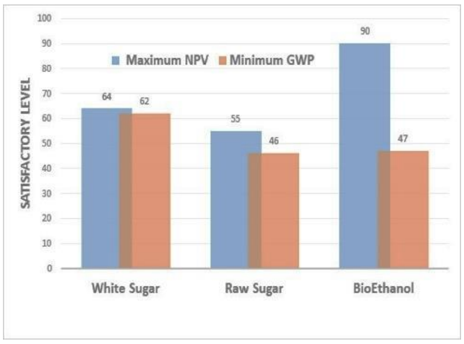

Fig. 5 Satisfaction level of Products Demand

The results show the maximum satisfaction level of products demand with a maximum expected NPV and minimum expected GWP conditions (Fig. 5).

6 Conclusions

A MILP formulation to address the retrofitting problem of a multi-resource based energy integrated SC under uncertainty has been presented. The model produces a set of feasible energy/material networks addressing the optimization of conflictive objectives. The capabilities of the model are highlighted through its application to a case study. The proposed stochastic approach maximizes the expected profit while satisfying a minimum environmental impact for each scenario. The interaction between the objectives has been shown. This way of generating feasible configurations will help the decision-maker to determine the best design according to the selected objectives. In this particular case, the results show that 100% of internal energy demand and 94% of biofuel demand can be met by an entirely renewables-based process network, which majorly generates energy by cogeneration unit and wind power.

References

Alabert, A., Somoza, A., De La Hoz, J., & Graells, M. (2016). A general MILP model for the sizing of islanded/grid-connected microgrids. *2016 IEEE International Energy Conference, ENERGYCON 2016*. http://doi.org/10.1109/ENERGYCON.2016.7514112

Čuček, L., Martín, M., Grossmann, I. E., & Kravanja, Z. (2011). Energy, water and process technologies integration for the simultaneous production of ethanol and food from the entire corn plant. *Computers and Chemical Engineering*, *35*(8), 1547–1557. http://doi.org/10.1016/j.compchemeng.2011.02.007

Illukpitiya, P., Yanagida, J. F., Ogoshi, R., & Uehara, G. (2013). Sugar-ethanol-electricity co-generation in Hawai’i: An application of linear programming (LP) for optimizing strategies. *Biomass and Bioenergy*, *48*, 203–212. http://doi.org/10.1016/j.biombioe.2012.11.003

Martín, M., & Grossmann, I. E. (2017). Optimal integration of a self sustained algae based facility with solar and/or wind energy. *Journal of Cleaner Production*, *145*, 336–347. http://doi.org/10.1016/j.jclepro.2017.01.051

Martín, M., & Grossmann, I. E. (2018). Optimal integration of renewable based processes for fuels and power production: Spain case study. *Applied Energy*, *213*(November 2017), 595–610. http://doi.org/10.1016/j.apenergy.2017.10.121

Mele, F. D., Kostin, A. M., Guillén-Gosálbez, G., & Jiménez, L. (2011). Multiobjective Model for More Sustainable Fuel Supply Chains. A Case Study of the Sugar Cane Industry in Argentina. *Industrial & Engineering Chemistry Research*, *50*(9), 4939–4958. http://doi.org/10.1021/ie101400g

Morakabatchiankar, S., Hjaila, K., Mele, F. D., Graells, M., & Espuña, A. (2018). Economic and environmental benefits of waste-based energy closed-loop integration in process industries under uncertainty. In *Computer Aided Chemical Engineering* (Vol. 43, pp. 501–506). Elsevier.

Prasad, A. A., Taylor, R. A., & Kay, M. (2017). Assessment of solar and wind resource synergy in Australia. *Applied Energy*, *190*, 354–367. http://doi.org/10.1016/j.apenergy.2016.12.135

Vidal, M., & Martín, M. (2015). Optimal coupling of a biomass based polygeneration system with a concentrated solar power facility for the constant production of electricity over a year. *Computers and Chemical Engineering*, *72*, 273–283. http://doi.org/10.1016/j.compchemeng.2013.11.006

Zukunft, F. (2014). Process News, (4). Retrieved from https://www.industry.siemens.com/topics/global/en/magazines/process-news/archive/Documents/en/process-news-2014-1_en.pdf