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Integrated Design, Planning, and Scheduling of Renewables-based Fuels and Power Production Networks

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Abstract

In this work, we optimize the design of renewables-based process networks for integrated fuels and power production, where a major challenge lies in the strongly time-dependent availability of renewable energy sources; it is thus vital to make detailed operational considerations already at the design stage. We propose a mixed-integer linear programming (MILP) formulation that combines a superstructure-based network synthesis model and an integrated planning and scheduling model. In the case study, in which the model is applied to a city in Spain, we demonstrate the effectiveness of the proposed framework and discuss the synergies that can be achieved with the resulting integrated energy system.

Keywords: Renewable energy, power production, biofuels production, integrated design and operation, process network

1. Introduction

In the light of increasing energy demand and climate change, increased efforts are being made in shifting from fossil to renewable energy sources. The European Union's Renewable Energy Directive has set a target of 20 % energy consumption from renewable sources by 2020. To achieve this goal, it is crucial to establish integrated energy systems that effectively harness synergies between various processes (Yuan and Chen, 2012).

When it comes to the design of purely renewables-based energy systems, most existing works focus either on the production of fuels or on the generation of power. Only recently, Martín and Grossmann (2017) have considered the synthesis of process networks consisting of renewables-based energy conversion processes for both fuels and power production. However, although the proposed model helps identifying the opportunities in such integrated process networks, it cannot consider effects at the operational level, which may have a significant impact on the design of the processes.

As highlighted by Zhang and Grossmann (2016), considering process dynamics is particularly important in situations in which time-sensitive electricity prices and loads have to be taken into ~~accounted~~. However, for design and long-term problems, applying detailed operational constraints to the entire time horizon inevitably leads to prohibitively large models; hence, multiscale models have been proposed in order to maintain the tractability of such problems (Mitra et al., 2014; Samsatli and Samsatli, 2015; Zhang et al., 2017).

The objective of this work is to optimize the design of process networks for fuels and power production that solely make use of renewable energy sources. As shown in Sections 2 and 3, we combine a superstructure-based network synthesis model and an integrated planning and scheduling model in a multiscale framework, which considers a planning horizon of one year and incorporates operational decisions at the hourly level. The proposed framework is applied to Almería, a city in the southeast of Spain, for which preliminary results are presented and discussed in Section 4.

2. Superstructure Network

We consider the superstructure network proposed by Martín and Grossmann (2017), as shown in Figure 1. The given network consists of two types of nodes: process nodes and resource nodes. Each process converts a specific set of input resources into its output resources. Process and resource nodes are connected by arcs, which depict the directions of the material or energy flows. The superstructure represents a superset of the set of feasible process networks, which can be generated by selecting different combinations of process and resource nodes.

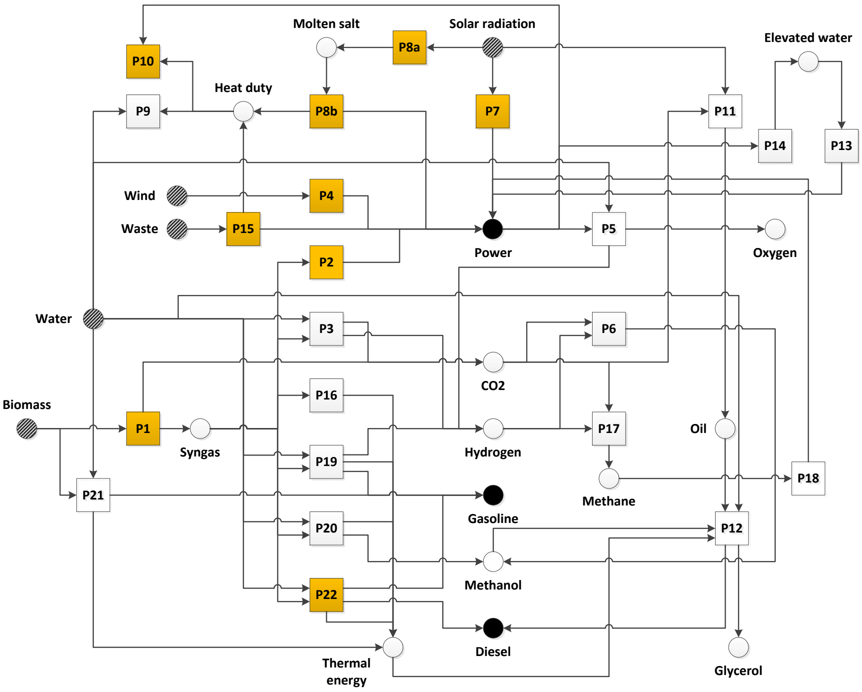

Figure 1: Superstructure network for renewables-based fuels and power production.

As input resources for the whole energy system (indicated by hatched resource nodes), we only consider renewable energy sources, such as wind, solar, hydro, biomass, and waste. Lignocellulosic biomass can be biochemically (P21) or thermally (P1) processed to bioethanol or syngas, respectively. Syngas can be further processed into hydrogen and CO_2 through a water-gas shift reaction (P3) or directly used to produce power (P2), hydrogen (P19), ethanol (P19), methanol (P20), Fischer-Tropsch liquids (P22), or simply thermal energy (P16). Wind is used for power generation (P4), and solar energy can be captured using photovoltaic (PV) panels (P7) or mirrors using concentrated solar power (CSP) technologies (P8a). Hydropower offers a way to store power by elevating water and maintaining its potential energy (P14), which is converted into kinetic energy (P13) when power needs to be generated. Furthermore, waste can be used to produce biogas, with which power can then be generated using a gas and a steam turbine (P15). Through electrolysis (P5), power can be used to produce hydrogen, which in turn can serve as input resource for methanol (P6) or methane (P17) production. While methane can further be used in a gas turbine (P18), methanol is processed in the transesterification of oil (P12). The oil can be extracted from algae (P11), which require sun light and CO_2 to grow. Finally, cooling processes are also included in the network in order to remove the heat generated by some processes (P9, P10).

The filled resource nodes in Figure 1 indicate resources for which given demands have to be satisfied: gasoline, diesel, and power. The highlighted processes depict the optimal network resulting from the case study (see Section 4).

3. Model Formulation

In the following, we briefly outline the main features of the proposed MILP formulation.

3.1. Time Representation

In the proposed multiscale time representation, which is illustrated in Figure 2, the planning horizon (in this case a year) is divided into seasons, denoted by index h. The set of seasons, H, is specified according to the reoccurring patterns that characterize the different time-varying parameters; hence, the seasons can also have different lengths. Each season h consists of a representative set of time periods, $\overline{T}_h$, which starts at time point 0. Time periods considered before time 0 are used to track past mode transitions. In each season h, a cyclic schedule over the given set of time periods is applied n_h times.

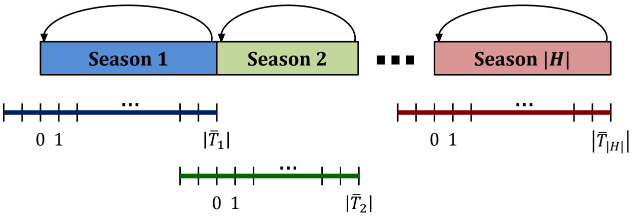

Figure 2: Multiscale time representation.

3.2. Network Design Constraints

The network design is given by the selected process (i) and resource (j) nodes, which represent production and storage facilities, respectively. We define the binary variable x_i that equals 1 if process i is selected. Similarly, the binary variable $\bar{x}_j$ equals 1 if a storage facility is built. The following constraints limit the capacities ($C_i, \overline{C}_j$) that can be realized:

$$C_i \leq C_i^{\max} x_i, \quad x_i \in \{0,1\} \quad \forall i \tag{1a}$$

$$\overline{C}_j \leq \overline{C}_j^{\max} \bar{x}_j \quad \bar{x}_j \in \{0,1\} \quad \forall j. \tag{1b}$$

3.3. Mode-based Scheduling Constraints

The following scheduling formulation is adapted from the discrete-time model proposed by Zhang et al. (2016), which is based on the assumption that each process in the network can operate in a given set of operating modes. While Eqs. (2a)–(2d) are simple mass balance constraints, Eqs. (2e)–(2j) describe the mode-based operation and constrain the transitions between different operating modes:

$$Q_{jht} = (1-\varepsilon_{jh}) Q_{jh,t-1} + \sum_i \rho_{ijht} P_{iht} + B_{jht} - S_{jht} \quad \forall j, h, t \in \overline{T}_h \tag{2a}$$

$$P_{iht} \leq \eta_{iht} C_i \quad \forall i, h, t \in \overline{T}_h \tag{2b}$$

$$Q_{jht} \leq \overline{C}_j, \quad B_{jht} \leq B_{jht}^{\max} \quad \forall j, h, t \in \overline{T}_h \tag{2c}$$

$$S_{jht} \geq D_{jht} \quad \forall j \in \bar{J}, h, t \in \overline{T}_h, \quad S_{jht} = 0 \quad \forall j \in \hat{J}, h, t \in \overline{T}_h \tag{2d}$$

$$\sum_{m \in M_i} y_{imht} = x_i, \quad P_{iht} = \sum_{m \in M_i} \overline{P}_{imht} \quad \forall i, h, t \in \overline{T}_h \tag{2e}$$

$$C_{im}^{\min} y_{imht} \leq \overline{P}_{imht} \leq C_{im}^{\max} y_{imht}, \quad y_{imht} \in \{0,1\} \quad \forall i, m \in M_i, h, t \in \overline{T}_h \tag{2f}$$

$$\sum_{m' \in \overline{TR}_{im}} z_{im'mh,t-1} - \sum_{m' \in \widehat{TR}_{im}} z_{imm'h,t-1} = y_{imht} - y_{imh,t-1} \quad \forall i, m \in M_i, h, t \in \overline{T}_h \tag{2g}$$

$$z_{imm'ht} \in \{0,1\} \quad \forall i, (m,m') \in TR_i, h, t \in \overline{T}_h \tag{2h}$$

$$y_{im'ht} \geq \sum_{k=1}^{\theta_{imm'}} z_{imm'h,t-k} \quad \forall i, (m,m') \in TR_i, h, t \in \overline{T}_h \tag{2i}$$

$$z_{imm'h,t-\bar{\theta}_{imm'm''}} = z_{im'm''ht} \quad \forall i, (m,m',m'') \in SQ_i, h, t \in \overline{T}_h. \tag{2j}$$

3.4. Continuity Constraints

Continuity equations are required at the boundaries of each season in order to maintain mass balance and feasible transitions:

$$y_{imh,0} = y_{imh,|\overline{T}_h|} \quad \forall i, m \in M_i, h \tag{3a}$$

$$z_{imm'ht} = z_{imm'h,t+|\overline{T}_h|} \quad \forall i, (m,m') \in TR_i, h, -\theta_i^{\max} + 1 \leq t \leq -1 \tag{3b}$$

$$y_{imh,|\overline{T}_h|} = y_{im,h+1,0} \quad \forall i, m \in M_i, h \in H \setminus \{|H|\} \tag{3c}$$

$$z_{imm'h,t+|\overline{T}_h|} = z_{imm',h+1,t} \quad \forall i, (m,m') \in TR_i, h \in H \setminus \{|H|\}, -\theta_i^{\max} + 1 \leq t \leq -1 \tag{3d}$$

$$\overline{Q}_{jh} = Q_{jh,|\overline{T}_h|} - Q_{jh,0} \quad \forall j, h \tag{3e}$$

$$Q_{jh,0} + n_h \overline{Q}_{jh} = Q_{j,h+1,0} \quad \forall j, h \in H \setminus \{|H|\} \tag{3f}$$

$$Q_{j,|H|,0} + n_{|H|} \overline{Q}_{j,|H|} \geq Q_{j,1,0} \quad \forall j. \tag{3g}$$

The cyclic schedules are enforced by applying Eqs. (3a)–(3b) while Eqs. (3c)–(3d) match the state in which the system is at the end of one season to the beginning of the next. Also, by adding Eqs. (3e)–(3g), we allow excess inventory ($\overline{Q}_{jh}$) accumulated over the course of a season to be carried over to the next.

Finally, the objective is to minimize the total annual cost, which consists of capital and operating expenses, for which piecewise-linear approximations have been incorporated.

4. Case Study

We apply the proposed model to Almería, a city in the southeast of Spain, for which the data are given in Martín and Grossmann (2017). We divide the planning horizon into four seasons, each represented by a week with an hourly time discretization, which results in an MILP with 117,838 continuous variables, 485,895 binary variables, and 486,388 constraints. The model was implemented in Julia with the JuMP package (Lubin, M., Dunning, 2015) and was solved to 0.6 % optimality gap in one hour using CPLEX 12.7 on an Intel® Core™ i7-2600 machine at 3.40 GHz with 8 processors and 8 GB RAM.

We specify that 5 % of the gasoline and diesel demand and 50 % of the power demand in Almería have to be met by the renewables-based process network. As shown in Figure 1, the solution suggests producing syngas from biomass and applying the Fischer-Tropsch process to produce gasoline and diesel. Power is generated by a syngas-driven gas turbine, PV panels, a CSP plant, wind turbines, and enzymatic digestion of waste. The total annual capital and operating costs amount to € 38.4 million and € 19.3 million, respectively. The breakdown of the costs into the different processes is shown in Figure 3.

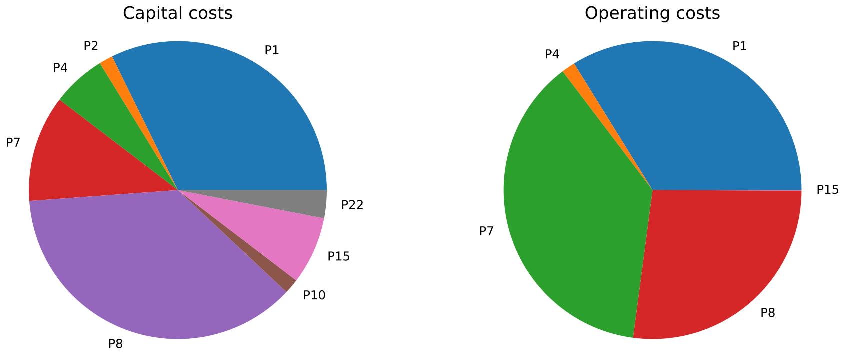

Figure 3: Breakdown of capital and operating costs into the selected processes.

Figure 4 shows the amount of power generated by each process and the amount of energy stored in the form of molten salt. We can clearly see that CSP allows solar power to be used over the course of the entire day. During the day, PV panels generate power while the molten salt section of the CSP plant is used to store solar power. Then at night, the stored energy is released to continue producing power. In overall, the CSP plant generates almost 50 times as much power as the PV panels. Compared to solar power, the amount of power that can be generated from wind is relatively small at this location. Moreover, we find that no more than 5 % of the gasoline and diesel demand can be covered with the current specifications, which is mainly due to the shortage of biomass.

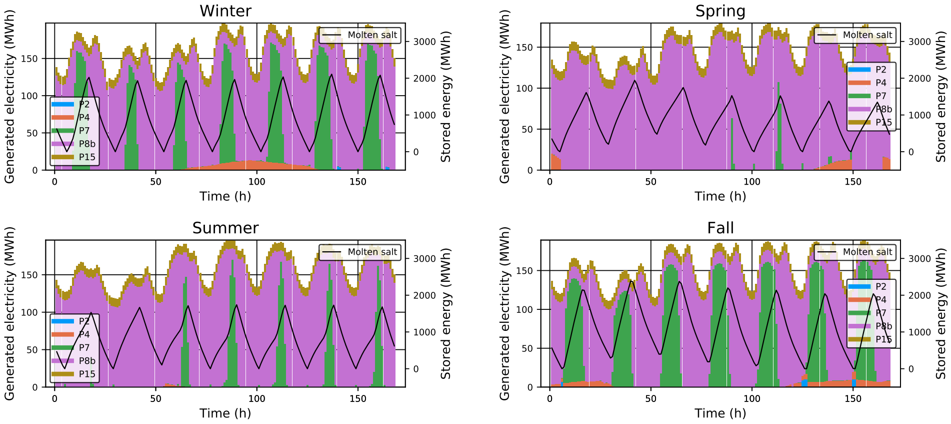

Figure 4: Amount of electricity generated by each process and stored.

5. Conclusions

In this work, we have developed a multiscale MILP model for the integrated optimal design and operation of renewables-based fuels and power production networks. The proposed model allows the selection of a feasible process network derived from a given superstructure network, while simultaneously optimizing detailed operational schedules for the selected processes. By applying the model to a case study for a particular location in Spain, we have identified the potential of CSP as energy storage and the bottleneck (biomass availability) for fuels production at this location.

Future work will involve exploiting further synergies by simultaneously optimizing such process networks for multiple geographical regions, and the development of solution algorithms for solving these large-scale problems more efficiently.

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