

Energy Supply Chain Optimization under Demand Variation and Emission Constraints

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Energy supply chains aim to ensure an uninterrupted satisfaction of energy demand at various forms with the maximum efficiency, while satisfying constraints on emissions released to the environment. The present work offers a framework for the optimization of the operating conditions in energy supply chains enriched with the option to optimally allocate new polygeneration units within an existing network so that stringent emission control policies are satisfied. The energy supply network involves a supply layer that includes energy resources available for polygeneration such as fossil fuels, biomass in different forms, solar and wind. The resources can be utilized by the energy supply network at various energy polygeneration units that include gas turbines, boilers and steam turbines, PV panels, wind generators and so forth. Within each unit, energy can be converted in various forms (e.g., electric power, steam of variable quality,) dictated by the overall demand and the decisions taken at the optimization level. The behavior of the system is monitored over a time horizon that enables the feasibility of the network to achieve the production quotas and satisfy the emission requirements. The decision support framework enables the optimal operation through structural changes in the network and assignment of suitable production targets for the individual units.

1. Introduction

Energy supply chains aim to ensure an uninterrupted satisfaction of energy demand at various forms with the maximum efficiency, while satisfying constraints on emissions released to the environment (Klemeš et al, 2005). To this extent, energy supply chains have incorporated various energy resources including biomass and other renewable energy sources to traditional and conventional resources such as coal, natural gas and other fossil fuels in order to reduce hazardous pollutants and other greenhouse gases. Numerous approaches investigate the spatial allocation of biomass and other renewable energy sources units for the improved performance of existing energy supply chains (Lam et al., 2009 and 2010; Leduc et al., 2010). Other research works focus on the design aspects of polygeneration units that are mainly governed by the strong interaction of chemical synthesis and power generation (Liu et al., 2010; Pistikopoulos et al., 2010). The efficiency of process systems engineering tools in the synthesis and

design of energy systems and in particular biorefineries is investigated by Kokossis and Yang, 2010.

The current approach aims at determining critical decisions in the performance of an energy supply chain both at the strategic and the operating level. Energy supply chain is considered as the distributed production of power, heat and chemicals by a set of fixed polygeneration units utilizing different resources. The strategic level involves decisions regarding the introduction of new energy polygeneration units into an existing infrastructure through targeted investments. The outlined decisions involve the operating conditions and participation in the generation of energy products of existing or newly introduced units in an annual basis for the satisfaction of the demand for power, heat (in the form of steam at different pressure levels and chemicals) under significant variability. The proposed optimization framework enables the identification of demand driven highly performing solutions through the direct consideration of all interacting factors within the energy supply chain over a future time horizon.

2. Optimization framework for energy supply chains

The present work offers a framework for the optimization of the operating conditions in energy supply chains enriched with the option to optimally allocate in time new polygeneration units within the energy supply network so that stringent demand profiles and emission control policies are fully satisfied. The energy supply network involves a resources layer that includes energy resources available for polygeneration such as fossil fuels, biomass in different forms (e.g., pellets of various biomass stocks, gasification of lignocellulosic residues), solar, wind, geothermal and hydro energy resources. The resources can be utilized by the energy supply network at various energy polygeneration units that include gas turbines, boilers and steam turbines, PV panels, wind generators and so forth. Within each polygeneration unit, energy can be converted in various forms (e.g., electric power, steam of variable quality, cooling, chemicals) as dictated by the overall demand profiles and the decisions taken at the optimization level. The demand of the various forms of energy behaves stochastically and is modeled with a non-stationary time series model. Each polygeneration unit produces as side-products emissions (e.g., greenhouse emissions, NO_x) that are monitored by regulating agencies and local legislation. A schematic of the super-structure of an energy supply chain under consideration is shown in Figure 1.

The optimization of the supply chain is performed at two different modes: (a) The operational level, where the operating decisions regarding the distribution of the energy products (including chemicals) coming out of each individual unit and the overall utilization of the polygeneration unit in the distributed production scheme is determined and (b) the strategic level, where decisions about the incorporation of new polygeneration units to an existing energy supply chain are taken. In the operational level, variability in the supply and the prices of the raw materials and the energy demand are taken into direct consideration for a fixed structure of the energy conversion network and emission constraints for a time horizon extended into the future. The time horizon enables the feasibility of the network to achieve the production quotas and satisfy the emission requirements. In the strategic level, the decision periods become

larger than in the operating level study but for a flexible network structure. The main objective is therefore the identification of suitable conditions for the introduction into an existing energy supply chain in terms of economic benefit of energy conversion units that utilize renewable energy sources.

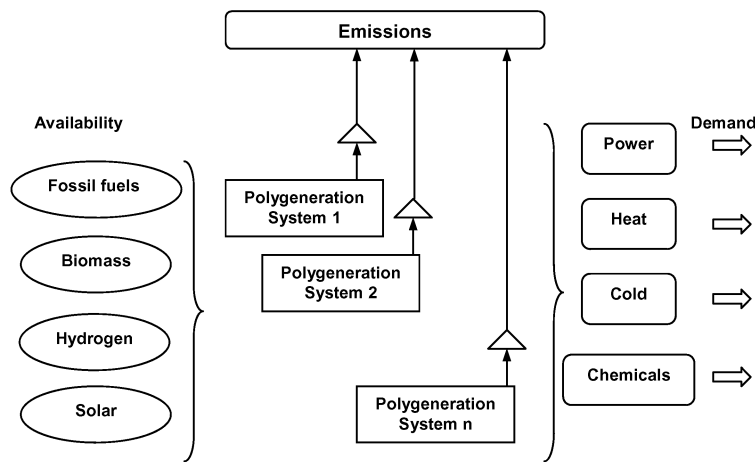


Figure 1: Energy supply chain schematic.

The prediction of the behaviour of the polygeneration infrastructure is achieved through the employment of simplified models. The characteristics of the various polygeneration systems at different operating modes are studied using the rigorous process simulator Aspen Plus (www.aspentech.com). Regressed equations are then derived using the predictions of the process simulator, thus relating the heat and power generation quantities with the required raw materials for the capacity range and the operating modes of interest. Similarly, CO₂ capture plants based on CO₂ absorption by suitable amine blends are considered. The introduction of additional more complex polygeneration units is therefore straightforward as the required modelling information can be derived from validated process model simulations. Estimates of the investment and the operating costs for new and existing units enable the rigorous evaluation of alternative design options. The optimization is performed over a future time horizon so that the effects of decisions at an early time can be assessed. For instance, the total capacity for new units introduced into the system is not based only on current needs but also on future needs both in demand and emissions specifications. Therefore, the decisions are not obtained with a myopic view of the situation but rather based on an overall performance over the selected time span.

3. Simulated results

3.1 Case study I – without CO₂ capture option

In this scenario an energy island that consists of numerous industrial and domestic consumers is considered with electric power requirements for the base year equal to

280,000 MWh/y, whereas the steam demand (10 bar and temperature 190°C) equals 64.8 t/hr. The permitted CO₂ emissions are set at 336,970 t/y. It is assumed that each year for the next 7 years, the requirements for electric power are increased at a rate of 5% per annum (the increase refers to the average value for the power demand) and the steam demand increases at a rate of 5% per annum. Concurrently, the permissible levels of CO₂ decrease at a rate of 10% each year. The system involves the use of lignite-, natural gas- and diesel-fired power generation units.

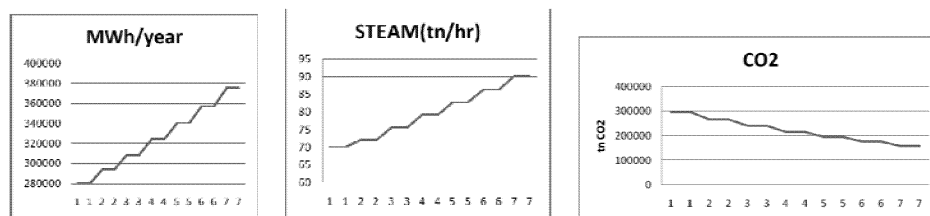


Figure 2. System requirements for electricity, steam and CO₂ emissions.

The objective function is the net present value of the system over a seven year period. The annual cash flows involve the cost of raw materials and the depreciation of investments in renewable energy sources. It is assumed that the power generation units on fossil fuels have been fully depreciated and the full satisfaction of demand generates a fixed stream of revenues each year. At the base year the demand is satisfied with a lignite-fired power plant, a natural gas-fired power plant and a diesel-fired power plant. Emissions regulations are imposed as hard constraints in the optimization problem. Alternative heat and power generation units involve a combined heat power unit utilizing biomass pellets as fuel, wind generators and photovoltaic.

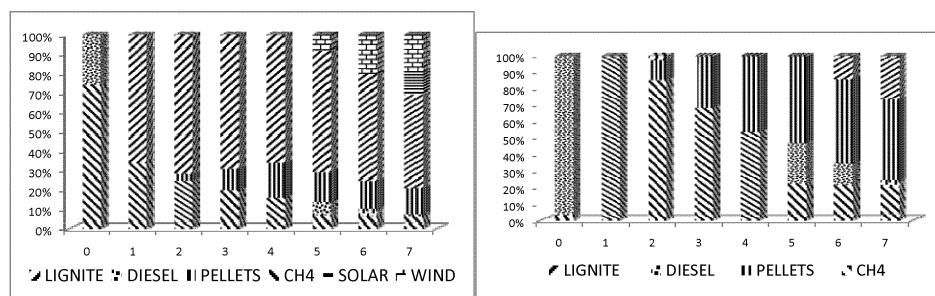


Figure 3: Distribution of electricity (left) and steam (right) production for scenario I.

The nonlinear optimization problem is solved with GAMS (www.gams.com). Figure 3 shows the distribution of electric power and steam production for the 7 y period of investigation with year 0 designating the base year. In this scenario lignite, diesel and natural gas dominate as fuels in the first year. However, the regulated reduction of the CO₂ emissions in the first year shifts the distribution towards natural gas to meet the specification. In the second year, a heat-power co-generation unit based on biomass pellets is introduced to increase the flexibility of the system to the emissions

specifications. Biomass pellets replace mainly lignite-fired production. In subsequent years, biomass pellets contribution as a fuel is further increased until it reaches the maximum capacity (70,000 t pellets/y) based on the decision for the overall investment on biomass pellets-fired steam turbine. In the third and fourth year, the production of energy from lignite continues to decrease, while the natural gas-fired turbine operates at the maximum capacity.

In the fifth year, the production from the lignite-fired plant is further decreased, while the production of energy from natural gas remains unchanged. Meanwhile, electricity generation from pellets is reduced to cover for the demand in high pressure steam. Therefore, the diesel-fired plant contributes to meet the target. At this point, the introduction of a set of wind generators is also judged as economically beneficial for the entire network. Finally, in the last two years a small increase in wind and solar energy is observed in order to satisfy the stringent constraint on CO₂ emissions.

3.2 Case study II – CO₂ capture option

In this scenario, the CO₂ emissions can be reduced by a combination of units based on renewable energy sources and CO₂ capture plants. CO₂ capture is achieved via gas absorption of the post-combustion stream by a liquid stream consisted of suitable solvents (usually a blend of amines). A second column regenerates the liquid solvent to eliminate the solvent requirements in the plant but at the expense of higher thermal duties utilized for the evaporation of the solvent mixture. CO₂ capture plants via absorption impose a significant load in the objective function mainly associated with the investment cost but also with the operating costs as a 10-15% of the heat generated is utilized in the solvent regeneration stage. However, it is expected that the CO₂ capture units will enable the prolonged utilization of low cost conventional coal-fired plants (e.g., lignite) thus avoiding expensive investment in renewable energy sources (e.g., PV or wind parks). The system demand and emission requirements remain as in scenario I.

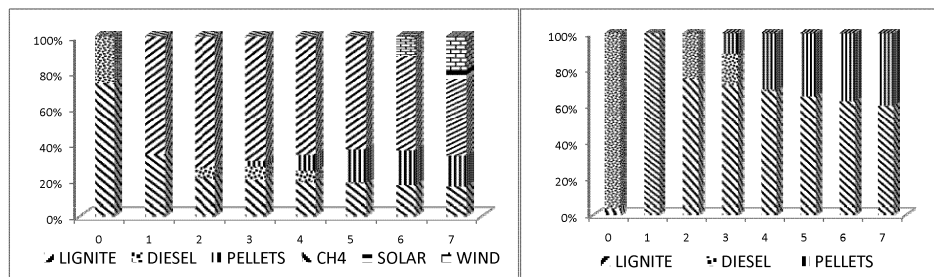


Figure 4: Distribution of electricity (left) and steam (right) production for scenario II.

Figure 4 shows the distribution of energy sources used for the satisfaction of the demand in the various forms of energy. Clearly, in scenario II the use of lignite-fired power plants is dominant over the entire time span. A CO₂ capture plant is introduced in the first year that enables the prolonged use of lignite without violating the emissions limits. The introduction of alternative carbon neutral fuels such as biomass pellets becomes much more modest than in scenario I. A similar trend is observed for the introduction of other renewable energy sources such as wind and solar. Compared to

scenario I, the percentage of wind and solar contribution is significantly reduced and shifted further away into the seven year horizon.

4. Conclusions

An optimization framework for the determination of strategic and operational level decisions for an energy conversion system that consists of various polygeneration units based on diverse fuels is proposed. The framework enables the optimal temporal allocation of new production units and the optimal distribution of the production tasks among the available energy conversion units under demand variability and emissions constraints. However, economic viability is an additional dimension in the optimization problem. CO₂ absorption capture plants provide significant relief in terms of satisfying the control of emissions thus enabling the utilization of existing low cost coal-fired units. The proposed framework allows the determination of the proper time for the introduction of biomass-based, wind and solar energy conversion units. Further improvement in the optimization framework can be achieved through the consideration in the decision making of the uncertainty associated with raw material prices and the operating efficiency of the plants.

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