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# A multi-period mathematical model for simultaneous optimization of materials and energy on the refining site scale

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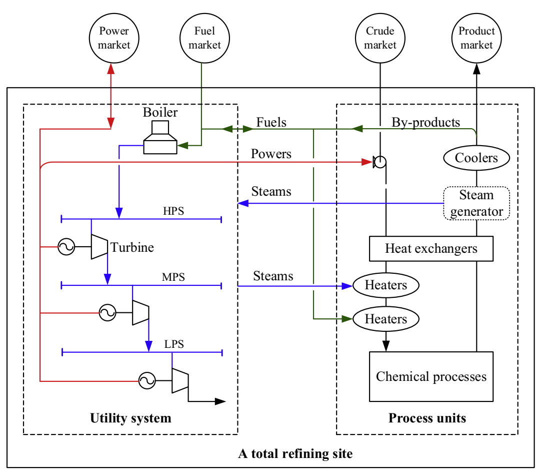
## HIGHLIGHTS

- Process units and utility systems are integrated for total refining site optimization.
- An MINLP model is presented to optimize materials and energy simultaneously.
- Energy requirements of process units are formulated based on transshipment model.
- The method does a good tradeoff between the material profit and energy cost.

## GRAPHICAL ABSTRACT

Integration between process units and utility systems.

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## ABSTRACT

A process system is designed for material transformations that produce certain functional chemicals while usually consuming large amounts of energy. Materials in process systems have long been the major focus of investigation to achieve better economic performance. Rising energy prices and stricter limitations on greenhouse gas emissions have also led to greater attention on energy savings. The configuration of process units in a total refining site has a great impact on both material and energy requirements. The simultaneous optimization of materials and energy is highly important for an enterprise. Hence, material and energy integration is proposed in this study for a total refining site to minimize costs. A mixed integer nonlinear programming model is developed that includes four parts: production planning for materials, energy requirements of process units on the basis of pinch analysis, operational planning for utility systems, and balance of utility streams in total sites. An industrial example is studied to demonstrate the performance of the proposed model and the advantages of simultaneous optimization of materials and energy. Significant economic benefits are demonstrated by the simultaneous optimization in this study.
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## 1. Introduction

People are changing their life styles and developing new technologies for a sustainable global society because of the rapid depletion of limited natural resources, such as fuel, energy, and water, and accelerated environmental deterioration. Process industries, producing numerous products to satisfy people's daily needs, are energy consumers. Therefore, it is crucial to achieve high economic performance while decreasing energy requirements in the process industries. In this study, we focus on refining processes, which are typical process industries. In this study, simultaneous optimization of materials and energy for refining processes is proposed to achieve high economic performance while reducing utility consumption.

A refining process is designed to transform crude oil into fuels and other chemicals. A large amount of energy is consumed in chemical reactions, material purifications, and transportation in a refining process. Energy is often degraded after its utilization in the chemical processes. The degraded energy can later be recovered by heat exchanger networks (HENs) or other auxiliary facilities. The interrelationships between material transformation and energy utilization in refining processes are demonstrated in Fig. 1. Material flow is indicated as the red lines, energy flow as the blue lines, and energy recycling as the green line. The vertical energy flow and the horizontal material flow intersect at "Reactions and Separations", where energy is utilized to conduct chemical reactions and purifications. The amount of energy required is closely related to the schedule of the flow sheet, throughput, and utility configuration in a refining process system. Separate optimization of materials and energy may not able to minimize cost. In this study, a mathematical model is formulated for both material transformations and energy requirements in refining process units, as well as for the energy balance in utility systems, to simultaneously optimize materials and energy in the process system. Energy requirements in process units are represented based on transshipment models.

Process industries have been widely studied for systematic energy savings. The research can be mainly categorized into flow sheet optimization [1,2], heat integration for a process unit or for a total site [3,4], HEN synthesis [5,6], and utility optimization [7,8]. Optimization of a process system involves process units, utility systems, and the integration of the two. Process units are used for material transformations and purifications. Considerable work has been done on the optimization of process units [9]. Linear programming (LP) was early introduced into refining process systems for production planning and scheduling [10]. The production planning and scheduling models were later expanded to consider multiple periods, variable crude supply, product demand, energy costs, and tank capacities [11,12]. Superstructures of process units were exploited to combine the property distribution of streams, and connections among process units were also optimized for a greater overall profit [13]. To represent the inherent nonlinearity of refining processes, more accurate nonlinear programming (NP) models were developed, especially for critical process units in refining processes. For example, the fractionation index model was introduced for a crude distillation unit (CDU) and formulated as a NP model. The NP model was then integrated into the refinery planning model [14,15]. CDU, fluid catalytic cracking unit (FCCU) and product blending models were formulated as NP models to investigate an industrial refining production planning problem [16]. These publications focused on flow rates and properties of materials in refining processes. Utility systems are isolated from the optimization models mentioned above. Energy costs were either ignored or computed by a given ratio to the throughput of process units, which may obtain suboptimal solutions to a total site due to the significant rise in energy prices.

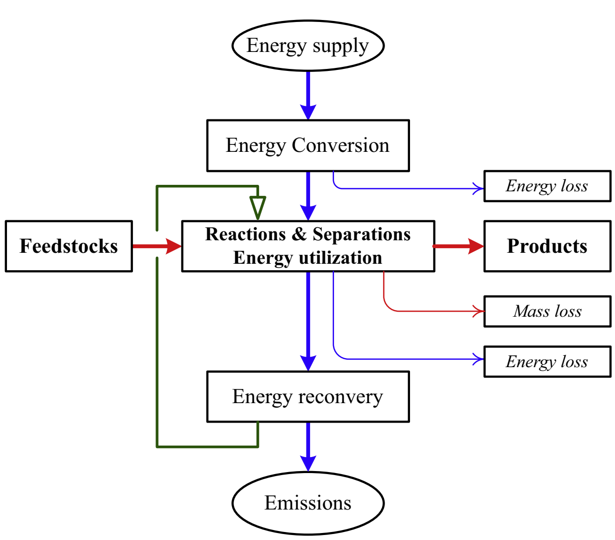


**Fig. 1.** View of materials and energy in a refining process system.

The synthesis and design of utility systems have been widely investigated by means of mathematical programming. The superstructures and mathematical frameworks of utility systems were proposed to optimize the configuration choices, equipment sizes and steam levels [17]. Modelling frameworks were investigated under variable conditions for flexible utility systems [18], and a methodology was then presented and applied to the design and operation of utility systems [19]. Operational planning of utility systems was formulated as a mixed integer nonlinear programming (MINLP) problem to meet utility demands in process units [20]. Graphical methods were also developed on the basis of pinch technology to determine the steam levels and the optimal configurations of utility systems [21,22]. Extended research in utility systems has generally focused on new turbine models [7], simultaneous utilization of single and multiple extraction steam turbines [23], and isentropic simulation for multiple extraction steam turbines [24]. Equipment reliability and availability considerations were also considered for the design and operation of utility systems [25], and these elements were also analysed for the flexibility of utility systems [26]. Graphical approaches were proposed to target emission reductions of utility systems [27], and then extended for energy resource planning of utility systems [28]. These works were only focused on an isolated utility system, in which steam and power demands are assumed to be a series of fixed parameters in their mathematical models. The assumption may not be able to represent real world operations because utility requirements change with the operation of process units in a total refining site.

Heat integration between process units and utility systems has been widely investigated on the basis of pinch analysis or mathematical programming [3]. The research includes site source-sink profiles (SSSP) to analyse the distributions of heat sources and sinks in a total site [29], site grand composite curves (SGCC) to incorporate the assisted heat transfer [30], and mixed integer linear programming (MILP) models to solve the optimal integration for a total site [31]. Recently, a retrofit framework for total site heat recovery systems was presented to determine the most cost-effective retrofit options and maximize potential savings, and a petrochemical site was tested [32]. The transshipment model was extended in some works to allow direct hot discharges/feeds between units for heat integration between process units and steam streams [33,34]. Heat integration between processes and utility systems were also investigated for some process industries, such as pulp and paper mill evaporation plants [35,36], juice processing plants [37], and industrial sawmill sites [38]. These works

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