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Multi-objective, multi-period optimization of biomass conversion technologies using evolutionary algorithms and mixed integer linear programming (MILP)

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ABSTRACT

The design and operation of energy systems are key issues for matching energy supply and demand. A systematic procedure, including process design and energy integration techniques for sizing and operation optimization of poly-generation technologies is presented in this paper. The integration of biomass resources as well as a simultaneous multi-objective and multi-period optimization, are the novelty of this work. Considering all these concepts in an optimization model makes it difficult to solve. The decomposition approach is used to deal with this complexity.

Several options for integrating biomass in the energy system, namely back pressure steam turbines, biomass rankine cycles (BRC), biomass integrated gasification gas engines (BIGGE), biomass integrated gasification gas turbines, production of synthetic natural gas (SNG) and biomass integrated gasification combined cycles (BIGCC), are considered in this paper. The goal is to simultaneously minimize costs and CO_2 emission using multi-objective evolutionary algorithms (EMOO) and Mixed Integer Linear Programming (MILP).

Finally the proposed model is demonstrated by means of a case study. The results show that the simultaneous production of electricity and heat with biomass and natural gas are reliable upon the established assumptions. Furthermore, higher primary energy savings and CO_2 emission reduction, 40%, are obtained through the gradual increase of renewable energy sources as opposed to natural gas usage. However, higher economic profitability, 52%, is achieved with natural gas-based technologies.

1. Introduction

In the perspective of increasing the share of renewable energies to mitigate global warming and with respect to the global issue of sustainable energy development, biomass has been increasingly focused on as a potential source of renewable energy. Poly-generation technologies, joined with the integration of biomass, have a good potential for CO_2 emissions reduction. Table 1 compares the lifecycle CO_2 emissions of biomass with other resources and shows the potential of biomass for CO_2 emissions reduction. This data is selected from the ecoinvent life cycle inventories database [1]. ΔCO_2 in Table 1 shows the CO_2 emissions of resources minus the CO_2 emissions of biomass. The biogenic carbon captured by photosynthesis is not accounted for the biomass CO_2 emissions. In addition, if any CO_2 mitigation technology is adopted [2], negative CO_2 emissions will be realized, which can reduce the emissions in the atmosphere [3].

In the present work, several options for integrating biomass in a poly-generation plant are studied, however before going forwards, a systematic optimization procedure is needed to select and size the equipments. The optimization of energy systems that include one or more technologies to meet the requirements of energy systems is extensively studied by many authors. It is referred to [4] for a detailed overview. From the author's point of view, the majority of studies can be divided into two main categories; the first category includes thermo-economic simulations and synthesis of biomass technologies and the second category includes optimization techniques for selecting and sizing equipments.

Researchers have paid much attention in the literature on thermo-economic simulations and synthesis of biomass technologies in cogeneration plants. A trigeneration system using a heat engine and a vapour compression chiller, running on biofuel, is simulated in [5] and a comparative analysis between the biofuel trigeneration and conventional fossil fuel was carried out. The energy and the exergy efficiencies of trigeneration system consisting

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Table 1
CO_2 Intensity of resources.

Resources	$CO_2 - Eq$ [1]: [kg/MJ]	ΔCO_2 [kg/MJ]
Electricity	0.3155	0.3071
Natural gas	0.0725	0.0641
Biomass	0.0084	0

of a biomass combustor, an ORC, a single-effect absorption chiller, and a heat exchanger are studied in [6] through a simulation. Process integration methodology and simulation is applied in [7] to deal with an application of a heat pump in energy systems for biomass gasification in a wood processing plant. For a detailed overview, simulation and modelling of biomass based cogeneration systems are reviewed in [8]. Most of these publications carried out only simulations, while system design optimization is neglected.

The second state of the art part of this work is on optimization techniques for selecting and sizing equipments. Diverse procedures exist to size cogeneration plants, like a structural optimization approach based on the mixed-integer linear programming [9]. Lyer and Grossmann [10] conducted a work on utility systems optimization for a multi-period operating condition by using a MILP method, however it was limited to the steam network model. Other researchers [11] developed a mono objective optimization model for the integration of cooling and heating systems based on the process integration and temperature intervals. A mono objective operations optimization and the design of trigeneration plants is also studied in [12]. Some limitations related to the simultaneous consideration of the economic evaluation and the CO_2 emissions assessment may appear in available optimization methods developed in [13] and [14]. Moreover, a mathematical programing model for selection and sizing of alternative equipments in a polygeneration scheme was investigated by researchers [15]. Three algorithms based on evolutionary and/or social metaphors for mono objective energy systems optimization problems were studied in [16]. An optimization tool for a district energy system design is presented in [17]. For a detailed overview, the role of optimization modelling techniques in power generation is reviewed in [18]. However, most of these optimization models only included a mono economic objective function, completed with environmental and energetic targets as constraints, rather than multi-objective optimization, as is done here.

To sum up, energy system analyses are extensively studied by many authors. However, a systematic procedure including process design and energy integration techniques with simultaneous consideration of multi-periods and multi-objective aspects for energy system designs is still missing. Considering all these concepts in a single optimization model defines a Mixed Integer non-Linear Problem (MINLP) with non differentiable equations due to the use of the temperature as decision variable in heat cascade constraints.

The purpose of the developed model in this paper is to use the decomposition approach to deal with this complexity. In order to do so, a multi-objective optimization model with evolutionary algorithms (EMOO) and MILP has been developed (sec.2).

In the developed model the features of both above mentioned types of study; the integration of biomass technologies' simulation models in the energy system as well as multi-objective optimization for sizing a cogeneration plant, are combined in a systematic procedure. This procedure evaluates the total costs and the CO_2 emissions simultaneously by decomposing the model into master and slave optimizations [19]. The considerations of several equipments as well as their thermodynamic properties (sec.3), including process design and energy integration techniques with simultaneous consideration of multi-periods and multi-objective aspects (sec.2.3), are important advantages in the present work. Finally, the developed model is demonstrated by means of a case study (sec.4). Results are compared to conclude advantages and disadvantages of alternative solutions (sec.4.1).

The energy system analyses could be divided into two major steps; first sizing and design optimization and second, operation optimization. The developed model in this paper is mainly used for the conceptual design and sizing optimization. The system configuration is optimized in this step. After that, the operation optimization will be done with more detailed modelling including a storage system, part load efficiency and advance control system by fixing the system configuration as an input data. Never the less this detail operation optimization is only possible if a feasible solution for a system configuration is obtained in the first step.

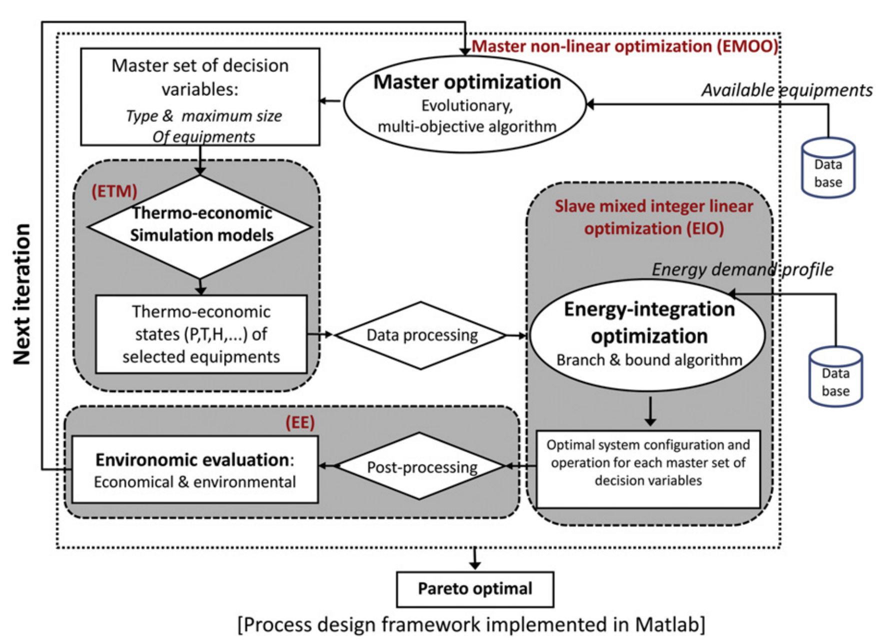

Fig. 1. Overall decomposition optimization sequence.