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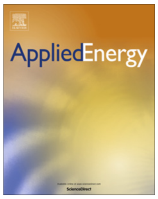

Optimization of a flexible multi-generation system based on wood chip gasification and methanol production

Christoffer Lythcke-Jørgensen [a,*], Lasse Røngaard Clausen [a], Loui Algren [b], Anders Bavnhøj Hansen [b], Marie Münster [c], Rasmus Østergaard Gadsbøll [d], Fredrik Haglind [a]

[a] Technical University of Denmark, Department of Mechanical Engineering, Denmark
[b] Energinet.dk, Section for Energy Analysis, Denmark
[c] Technical University of Denmark, Department of Management Engineering, Denmark
[d] Technical University of Denmark, Department of Chemical and Biochemical Engineering, Denmark

HIGHLIGHTS

- A flexible multi-generation system (FMG) is modelled and optimized.
- The FMG is based on an existing combined heat and power plant.
- Retrofit options include a methanol-producing biorefinery and heat pumps.
- The optimized design features a full-size biorefinery located next to industry.
- Results stress that operation uncertainties must be considered when designing FMG.

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ABSTRACT

Flexible multi-generation systems (FMGs) consist of integrated and flexibly operated facilities that provide multiple links between the different sectors of the energy system. The present study treated the design optimization of a conceptual FMG which integrated a methanol-producing biorefinery with an existing combined heat and power (CHP) unit and industrial energy utility supply in the Danish city of Horsens. The objective was to optimize economic performance and minimize total CO_2 emission of the FMG while it was required to meet the local district heating demand plus the thermal utility demand of the butchery. The design optimization considered: Selection, dimensioning, location and integration of processes; operation optimization with respect to both hourly variations in operating conditions over the year as well as expected long term energy system development; and uncertainty analysis considering both investment costs and operating conditions.

Applying a previously developed FMG design methodology, scalable models of the considered processes were developed and the system design was optimized with respect to hourly operation over the period 2015–2035. The optimal design with respect to both economic and environmental performance involved a maximum-sized biorefinery located next to local industry rather than in connection with the existing CHP unit. As the local industry energy demands were limited when compared to the biorefinery dimensions considered, process integration synergies were found to be marginal when compared to the economic and environmental impact of the biorefinery for the present case.

Assessing the impact of uncertainties on the estimated FMG performances, the net present value (NPV) of the optimal design was estimated to vary within the range 252.5–1471.6 M€ in response to changes of ±25% in investment costs and methanol price, and considering two different electricity price scenarios. In addition, a change in the interest rate from 5% to 20% was found to reduce the lower bound of the NPV to 181.3 M€ for reference operating conditions. The results suggest that the applied interest rate and operating conditions, in particular the methanol price, would have a much higher impact on the economic performance of the designs than corresponding uncertainties in investment costs. In addition, the study outcomes emphasize the importance of including systematic uncertainty analysis in the design optimization of FMG concepts.

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* Corresponding author at: Nils Koppels Allé 403, 2800 Kgs. Lyngby, Denmark.
E-mail address: celjo@mek.dtu.dk (C. Lythcke-Jørgensen).

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Nomenclature

Latin letters

C_0	net present value [M€]
$C_{inv,k}$	investment cost, process k [M€]
$C_{inv,k0}$	reference investment cost, process k [M€]
$c_{op,i}$	hourly operation result [M€/h]
$c_{op,k}$	operation cost, process k [M€/h]
p_f	power factor for economy-of-scale calculations [–]
r	interest rate [–]
T	number of years from installation date [–]
t_i	duration of period i [h]
$t_{PV,i}$	present value factor of period i [h]
Z_0	total CO_2 emission impact [MTon]
z_{op}	hourly CO_2 emission impact of operation [MTon]

Greek letters

σ	process dimension
ω	installation decision (integer)
λ	load

Subscripts

i	period
k	process

Abbreviations

CCHP	combined cooling, heat and power
CHOP	Characteristic Operating Pattern
CHP	combined heat and power
FMG	flexible multi-generation systems
NPV	net present value
RES	renewable energy sources
SOEC	solid oxide electrolysis cell
TCE	total CO_2 emission impact

1. Introduction

The transition towards sustainable energy systems based on intermittent renewable energy sources (RES) necessitates the development of efficient means for balancing generation and consumption of energy services. While focus previously was centred on developing smart grid technology for the power grid, recent studies suggests that the challenge of balancing generation from renewables is better appreciated from a holistic energy system perspective in order to avoid suboptimal, sector-based solutions [1,2]. This holistic approach has been referred to as a Smart Energy System approach, and it promotes the integration of power, thermal and gas grids, and the use of various energy storage options in combination in order to achieve secure and sustainable energy systems based on renewable sources [3].

However, synergies from integrating energy conversion process in multi-generation systems are not considered directly using the smart energy systems approach. These synergies may be of great importance in the transition towards sustainable energy systems [4], especially for biomass conversion where it has been suggested that systematic consideration of process integration synergies may increase the energy- and cost-efficiency of the conversion processes as well as the overall energy system [5].

Responding to this, the concept of flexible multi-generation systems (FMG) was recently introduced by Lythcke-Jørgensen et al. [6]. Here, FMGs were defined as integrated systems that generate multiple energy services and are able to adjust operation in response to fluctuating demand patterns and varying price schemes in the overarching energy system. The hypothesis is that local or regional FMGs may support the balancing of an energy system with large shares of variable RES in a cost-effective way by linking the different parts of the energy system with local supply systems. By converting energy in response to demand and price variations, FMGs may be regarded as virtual energy system valves as conceptually illustrated in Fig. 1, making the development of FMGs a relevant topic.

The development of FMGs is complex and involves multiple design aspects. Within these, five aspects are considered of special relevance:

1. Process selection and dimensioning
2. Systematic process integration
3. Variable short-term operation conditions, including hourly, diurnal, weekly and seasonal changes in demands and generation from variable RES
4. Variable long-term operation conditions, responding to developments in the energy system
5. Uncertainty analysis

Numerous approaches for designing multi-generation systems have been presented in literature [7,8], but as discussed in Lythcke-Jørgensen et al. [6], none of these are able to consider all five listed aspects coherently. For instance, Liu et al. [9] developed a stochastic, multi-objective mixed integer-nonlinear programming model for designing polygeneration[1] systems based on several previous works, but did not consider short-term operation or process integration. Based on the OSMOSE tool,[2] Maréchal et al. [12] presented a multi-period, multi-objective methodology for designing multi-generation systems which considered technology selection and dimensioning, process integration, selection of facility location selection, flexible operation, and network layout. Fazlollahi et al. developed three add-ons to the methodology to allow for the structured reduction of operation periods [13], inclusion of daily thermal storages [14] and detailed design of distribution networks [15]. However, the combined methodology only considered variations in one external operating condition, namely outdoor temperature, meaning that flexible interactions with other parts of the energy system were not considered. In addition, uncertainties were not addressed in the combined methodology. In consequence, a novel methodology for designing FMGs was introduced in Lythcke-Jørgensen et al. [6] which included all the listed aspects as well as others, including biomass supply chains.

A number of specific FMG concepts have been treated in case studies. Regarding FMGs integrating the heat and power layers, Lund et al. [2] presented the case of Skagen combined heat and power (CHP) plant which included three CHP units, thermal energy storage, a peak load gas boiler, and an electrical boiler. The system effectively created a dual link between the electricity grid and the district heating system as the plant was able to both

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[1] In a recent review, Adams and Ghouse [10] defined 'polygeneration' as a thermochemical process which simultaneously generates electricity and produces at least one type of chemical or fuel without being a co- or tri-generation unit.

[2] OSMOSE is a computer aided process engineering tool, developed at EPFL in the IPESE group, for designing and optimizing integrated energy systems. For more information, refer to [11] or the IPESE group homepage: http://ipese.epfl.ch/.

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