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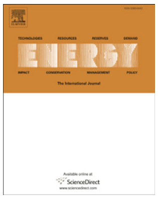

A methodology for designing flexible multi-generation systems

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ABSTRACT

An FMG (flexible multi-generation system) consists of integrated and flexibly operated facilities that provide multiple links between the various layers of the energy system. FMGs may facilitate integration and balancing of fluctuating renewable energy sources in the energy system in a cost- and energy-efficient way, thereby playing an important part in smart energy systems.

The development of efficient FMGs requires systematic optimization approaches. This study presents a novel, generic methodology for designing FMGs that facilitates quick and reliable pre-feasibility analyses. The methodology is based on consideration of the following points: Selection, location and dimensioning of processes; systematic heat and mass integration; flexible operation optimization with respect to both short-term market fluctuations and long-term energy system development; global sensitivity and uncertainty analysis; biomass supply chains; variable part-load performance; and multi-objective optimization considering economic and environmental performance.

Tested in a case study, the methodology is proved effective in screening the solution space for efficient FMG designs, in assessing the importance of parameter uncertainties and in estimating the likely performance variability for promising designs. The results of the case study emphasize the importance of considering systematic process integration when developing smart energy systems.

1. Introduction

FMGs (flexible multi-generation systems) are integrated, dynamic facilities that convert one or several energy resources into multiple energy services and other valuable products, e.g. electricity, heating, cooling, bio-fuels, and bio-chemicals [1]. FMGs are characterised by their ability to adjust operation in response to fluctuating demand patterns and varying price schemes. In the present work, the following definition of an FMG is introduced:

- A flexible multi-generation system (FMG) is a system of integrated facilities that provide multiple links between layers of the energy system, enabling adjustable operation in response to changes in prices and demands of the consumed and delivered services.[1]

The main advantages of FMGs are: The embedded possibility for optimizing operation by altering feedstock, products and services depending on demand and market price [2–4]; the possibility of integrating and balancing generation from intermittent renewable energy resources such as wind, solar, wave and tidal in a cost-efficient way [5,7], and the possibility of achieving high aggregated conversion efficiencies through process integration [8–11]. Through the conversion, conditioning and storing of multiple energy vectors, FMGs integrate the various layers of the energy

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[1] In specific cases, the definition of an FMG may be overlapping with the terms ‘polygeneration’ and ‘energy hubs’. In a recent review, Adams and Ghouse [75] have 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. ‘Energy hubs’ may refer to homes, large energy consumers, power plants or regions [76] as well as integrated facilities [4,77]. The FMG definition is introduced in order to characterize integrated facilities that may actively contribute to the balancing of the energy system.

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Nomenclature

Latin letters

A_a	Area size [km^2]
b	Number of parameter value levels in Morris screening [−]
C_{HEN}	Heat exchanger network investment cost [Euro]
$C_{inv,k}$	Process investment cost [Euro]
$C_{inv,k0}$	Process reference investment cost [Euro]
c_b	Marginal biomass cost [Euro]
c_{b0}	Reference biomass cost [Euro]
$c_{b,tr}$	Marginal biomass logistics cost [Euro]
c_{op}	Operating cost [Euro]
D_p	Uncertainty distribution of parameter p [−]
$d_{tr,a}$	Mean transportation distance from area a [km]
$\dot{e}_f$	Thermal energy flow [kW]
EE	Elementary effect [-]
f	Model output function
G_i	CHOP group
$\Delta H_{s,i}$	Sum of enthalpy flows in temperature interval s [kW]
i	Annual discount rate [−]
M	Number of uncertain model parameters [−]
M_f	Investment scaling constant [−]
$\dot{m}_f$	Mass flow [kg/s]
$mean_i$	Estimated standard error of the mean [−]
$N_{CHOP,max}$	Maximum number of CHOP groups [−]
n_p	Number of characteristic parameter intervals [−]
O_j	Operating point
p	Parameter
q_a	Annual biomass cultivation in area a [ton]
$q_{b,an}$	Annual biomass demand [ton]
R	Product or service market
R_{th}	Thermal energy market
R_b	Local biomass market
r_a	Maximum transportation distance, area a [km]
SEE	Sigma-scaled elementary effect [−]
s_{max}	Number of temperature intervals [−]
T	Temperature [°C]
t_i	CHOP group, duration [h]
t_j	Operating point, duration [h]
$t_{PV,i}$	CHOP group, present value factor [h]
w	Number of repetitions in Morris screening [−]
Y_j	Operating point, year of occurrence [−]
y_k	Installation delay of process k [years]
y_{lt}	Facility lifetime [years]
Z_0	Global warming potential [tCO$_2$]
z_{inv}	Global warming potential of investments [tCO$_2$]
z_{op}	Global warming potential of operation [tCO$_2$]

Greek letters

Δ	Perturbation factor in Morris screening [−]
$\lambda_{k,i}$	Process load of process k in period i [−]
$\nu_{k,i}$	Operation of process k in period i [−]
σ_k	Dimension of process k [−]
σ_{k0}	Process k reference dimension [−]
σ_{ut}	Utility process dimension [−]
ω_k	Installation decision for process k [−]

Subscripts

a	Biomass cultivation area index
b	Biomass flow index
f	Thermal and mass flow index
i	Period index
j	Operating point index
k	Process index
l	Layer index, used in the Mixed Integer-Linear Programming model
n	Characteristic parameter interval index
p	Parameter index
r	Market index
s	Temperature interval index
0	Reference

Abbreviations

AD	Combined anaerobic digester and biogas upgrading facility
BB	Biomass boiler
CCHP	Combined cooling, heating and power
CHOP	Characteristic operating pattern
CHP	Combined heat and power
DESS	Distributed energy supply system
FMG	Flexible multi-generation system
GB	Gas boiler
GT	Gas turbine
GWP100a	100-years global warming potential
HP	Ground-based district heating heat pump
LCA	Life cycle assessment
MILP	Mixed integer-linear programming
MINLP	Mixed integer-nonlinear programming
NPV	Net present value
SMG	Static multi-generation plant
SR	Steam Rankine cycle

system and are capable of providing supply-demand flexibility that can counteract energy system imbalances induced by e.g. intermittent renewable energy sources. In principle, FMGs can therefore be seen as efficient energy system valves that may play an important part in the development and operation of smart energy systems [12,13]. The generic FMG concept is illustrated in Fig. 1.

By definition, FMGs may be either centralized facilities or distributed systems, as long as the various facilities are integrated. The present manuscript differentiates between a *plant*, in which all considered facilities are co-located, and a *system*, in which facilities are distributed on several locations. It should be emphasized that FMGs may include static processes, e.g. cellulosic ethanol production [14] as well as intermittent processes that are not fully dispatchable, e.g. wind turbines and solar heating, as long as the combined system has a degree of operational flexibility.

The issues to be considered when designing FMGs comprise: The selection of processes and technologies from many alternatives; geographical location, dimensioning, and integration of processes with respect to thermal and mass flows; operation optimization with respect to hourly demand and price fluctuations and long-term energy system development; determination of local resource availability; investment planning; systematic evaluation of design uncertainties; and consideration of both economic and environmental objectives. All of these issues must be considered simultaneously as they affect one another. To cope with this complexity, a systematic optimization approach is needed for the design of FMGs [8].

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