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Incorporating combined cycle gas turbine flexibility constraints and additional costs into the EPLANopt model: The Italian case study

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The planning of an energy system with high penetration of renewables is increasing in complexity as only an effective implementation can allow the tackling of environmental and energy security issues. The aim of this study is to present the integration of combined cycle gas turbine cycling costs in EPLANopt, a simulation software consisting of EnergyPLAN coupled to a Multi-Objective Evolutionary Algorithm. The model is then applied to the Italian energy system which is characterized by a very high capacity and electricity production from combined cycle gas turbine systems. The proposed approach established a first step in the direction of modelling their role for load modulation accounting for technical constraints and additional costs related to start-up and partial load condition. Results show the importance of considering cycling costs of combined cycle gas turbine system within energy system modelling as the nature of these costs at the increasing of intermittent renewable generation can reach peaks of 33.5 €/MWh. Additionally, the inclusion of CCGT cycling costs in high penetration non programmable renewable energy sources scenarios opens up favorable business models for other load modulation strategies (e.g. electric batteries).

1. Introduction

In recent years, the development of energy scenarios and the planning of energy systems has become a highly relevant topic, as consequence of the environmental and security issues of energy systems. Policy makers need tools capable of simulating energy systems over the years to develop effective energy policies. Researchers that study the impact of the energy production and consumption on climate change need tools able to account for those aspects. Finally, developing Countries facing problems of energy access and security require modelling tools to plan energy systems to overcome those problems and to evaluate their impact on the local economies.

Energy system models represent a simplified picture of the real energy system and its costs. In literature, it is possible to classify two main approaches: top-down models, with focus on the economic theory, and bottom-up models, with focus on the technology analysis. A. Herbst et al. [1] present a review of these two approaches to the problem of energy system modelling. Both approaches present different advantages and limitations and develop a more detailed analysis on different aspects of the energy system. Many existing models for simulating and analyzing the integration of renewable energy into the energy system have been analyzed in detail by Connolly et al. [2]. The EnergyPLAN software [3] developed by Aalborg University and based on the bottom-up approach has resulted in one of the most complete tools to describe future energy system in a very short computational time [4]. EnergyPLAN is a deterministic input/output model that integrates the three primary sectors of any national energy system, (electricity, heat and transport sectors) thanks to predefined priorities [5]. This characteristic allows for a complete simulation of the interactions between different energy system sectors. The program is a descriptive and analytically programmed computer model for hourly base simulation of a regional or national energy system. High time resolution allows the modeler to catch the variability of non-programmable renewable energy sources. The EnergyPLAN

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Acronyms

CCGT	Combined Cycle Gas Turbine
UC	Unit commitment
SO	Single-Objective
MO	Multi-Objective
VRES	Variable renewable energy sources
CHP	Combined Heat and Power
HP	Heat Pump
MOEA	Multi-Objective Evolutionary Algorithm
MOO	Multi-Objective Optimization
PV	Photovoltaic
TSO	Trasmission system operator

Nomenclature

x	Set of all decision variables
m	Objective function index
f_m	m-th objective function
i	Decision variable index
x_i	i-th decision variable
$x_i^{(L)}$	Lower bound of i-th decision variable
$x_i^{(U)}$	Upper bound of i-th decision variable
k	Scenario index
Δ***Total annual costs***	Variation of the costs for scenario k with respect to the reference scenario [%]
Δ***Emissions***	Variation of CO_2 emissions for scenario k with respect to the reference scenario [%]
$\textbf{Total annual costs}_k$	Total annual costs of scenario k [M€]
$\textbf{Total annual costs}_{REF}$	Total annual costs of reference scenario [M€]
$\textbf{Emissions}_k$	Total annual CO_2 emissions of scenario k [Mt]
$\textbf{Emissions}_{REF}$	Total annual CO_2 emissions of reference scenario [Mt]
$\textbf{Total annual costs}_{\text{CCGT cycling}}$	Total annual costs due to cycling of combined cycle gas turbine systems [€]
$\textbf{StartUp}_{costs}$	Start-up costs [€]
$\textbf{DecayOfEfficiency}_{costs}$	Costs derived from partial load operation due to the decay of efficiency. [€]
$\textbf{Curtailments}_{costs}$	Costs due to the imperfect flexibility of the power system and the generated curtailments [€]
t	Time-step index
j	Type of start-up index
$\textbf{N\_StartUp}_{j,t}$	Number of starts per each time-step t and each type of start j
$\textbf{cost\_StartUp}_j$	Specific cost per each type of start j [€/MW]
Reference_plant	Size of the reference CCGT system [MW]
additional_fuel	Additional fuel due to partial load operation [MWh]
cost_NG	Cost of natural gas [€/MWh]
n	CCGT plant index
$\textbf{eff\_rel}_{t,n}$	Relative efficiency of each plant n (given by the curve in Fig. 2) at time-step t
eff_nom	The nominal efficiency of the reference CCGT plant (assumed equal to 55%)
$\textbf{Ongoing\_plants\_gen}_t$	The overall electricity generation from CCGT systems for each time-step t [MWh]
$\textbf{d}_t$	the hourly distribution of CCGT electricity production from EnergyPLAN [MWh]
$\textbf{costs}_{\textbf{CCGT cycling}}$	Specific costs for cycling of combined cycle gas turbine systems [€/MWh]
$\textbf{El\_p}_{CCGT}$	Total annual electricity production from combined cycle gas turbine systems [MWh]
$\textbf{costs}_{CCGT}$	Specific costs of combined cycle gas turbine systems [€/MWh]
$\textbf{Total annual costs}_{CCGT}$	Total annual costs of combined cycle gas turbine systems [€]

software does not readily find the best mix of technologies through an optimization process. The optimization of different technologies and sources within the energy system is a multi-objective problem because it concerns economical, technical and environmental aspects. The optimization analysis on these competing objectives produces a Pareto front of best solutions or future configurations of the energy system.

Bjelic et al. [6] have realized a soft-linking of EnergyPLAN software with a generic optimization program (GenOpt). This approach opens up the possibility to perform single objective optimization analysis and has been used to define the minimal increase in the costs of the total national energy system for Serbia under the EU 2030 framework. Mahbub et al. [7] have coupled EnergyPLAN to a multi-objective evolutionary algorithm written in Java to evaluate the Pareto front of best configurations of the energy system. Using a similar approach, EURAC research has developed the python model EPLANopt characterized by an open source code and documentation [8]. The model has been already presented in another paper [9] and for this reason is not matter of this study. However it is important to mention that the EPLANopt model is based on the simulation deterministic model, EnergyPLAN, developed by Aalborg University, coupled to a Multi-Objective Evolutionary Algorithm based on DEAP python library [10].

The scope of this paper is to apply this model to the Italian energy system incorporating combined cycle gas turbine (CCGT) flexibility constraints and additional costs in order to evaluate their future impact. The Italian energy system was considered as case study of the developed models since it is characterized by a very high capacity and electricity production from CCGT systems. In the future, their role for modulating the load might increase as an option to guarantee the national grid stability as well as the spinning reserve. The EnergyPLAN model considers CCGT systems, like the other power plants, as fully flexible power plants that can increase their production from 0 to 100% in a single hour independently from how many hours of stop had previously undergone. This is based on the assumption that in the future the power plants will reach a very high level of flexibility.

As shown in Table 1, several studies have inspected the impact of operational flexibility in energy system modelling. They are mostly characterized by hourly resolution unit commitment (UC) models that integrates flexibility requirements like ramp constraints, start-up costs and partial load operation. They almost entirely focus only on the power sector. This for this is that unit commitment models based on mixed integer linear programming applied to energy planning problems are characterized by a heavy computational burden [19].

Table 1 shows various approaches that tried to reduce the computational time through different techniques like integer clustering applied at unit commitment models. Even using these approaches the planning problem remains concentrated on the