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An integrated stochastic multi-regional long-term energy planning model incorporating autonomous power systems and demand response

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A B S T R A C T

The power sector faces a rapid transformation worldwide from a dominant fossil-fueled towards a low carbon electricity generation mix. Renewable energy technologies (RES) are steadily becoming a greater part of the global energy mix, in particular in regions that have put in place policies and measures to promote their utilization. This paper presents an optimization-based approach to address the generation expansion planning (GEP) problem of a large-scale, central power system in a highly uncertain and volatile electricity industry environment. A multi-regional, multi-period linear mixed-integer linear programming (MILP) model is presented, combining optimization techniques with a Monte Carlo (MCA) method and demand response concepts. The optimization goal concerns the minimization of the total discounted cost by determining optimal power capacity additions per time interval and region, and the power generation mix per technology and time period. The model is evaluated on the Greek power system (GPS), taking also into consideration the scheduled interconnection of the mainland power system with those of selected autonomous islands (Cyclades and Crete), and aims at providing full insight into the composition of the long-term energy roadmap at a national level.

1. Introduction

The power sector constitutes a significant part of the overall energy industry accounting for the electricity generation, transmission, and distribution processes. It consists of a complex infrastructure including a large variety of different types of power units, extensive electricity transmission and distribution networks, as well as a great deal of end-users with distinct energy consumption profiles. Power system operators are responsible for matching electricity supply and demand in the most economically efficient way in real time, guaranteeing simultaneously grid stability and reliability. Not surprisingly, the future growth of power demand is highly correlated with the evolution of a series of parameters, inclusive of economic growth rates, electricity prices, industrial and services activities, population growth (especially in the developing countries such as China, India, etc.), proportion of population having connection to the central power grid [1], levels of regional electrification etc. [2].

For many years, the primary goal of strategic GEP (generation expansion planning) has been to ensure power grid's stability and security, economic viability of the whole system, as well as to achieve reduction of energy dependence at a national and/or regional level. This multiplex task has been further complicated by the establishment of different power market structures (deregulated electricity markets) along with the consideration of environmental issues such as CO_2 emissions abatement and increased RES (Renewable energy technologies) penetration [3].

Long-term GEP provides the methodological framework so as to select the optimal type of power generation technologies to be installed in each location during each time period, as well as the optimal production levels of each power unit in each time interval. Numerous parameters have to be taken into account in order to assess and determine the optimal power mix for the satisfaction of electricity load. These are related to both technical and economic issues, including the basic technical characteristics of each technology (efficiency, availability, carbon footprint, etc.), economic terms (capital cost, fixed and variable operational and maintenance

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(O&M) cost, fuel cost, CO_2 emission pricing), access to finance and other energy resources, geographical location of each region, type of energy policies applied and energy potential in each country, existing installed capacity, interconnection capabilities with other neighboring countries, and power market regulations [2,4]. The impacts of demand-side management with rebound effect and smart grid technologies on GEP decisions have been also examined in Refs. [5,6].

Although cost minimization constitutes the typical objective function, there are works in the literature utilizing a multi-objective framework for the solution of GEP [7–9].

With regard to the GPS (Greek power system), the liberalization of electricity market along with the rapid penetration of natural gas (NG) and RES into the power system, and the diminishing share of the previously dominant lignite-fired power generation, have radically transformed the overall situation. Electricity trade has also played a noticeable role in the country's energy balance. Domestic lignite continues to be the main energy resource utilized for electricity generation, albeit at a decreasing rate, and followed by natural gas, hydroelectric energy, and other forms of RES (e.g., wind turbines, photovoltaics). According to the Greek Law 3851/2010, climate protection through the mitigation of greenhouse gas (GHG) emissions is of top priority in order for the country to meet its environmental targets. In this context, promotion and utilization of RES comprises a powerful tool for the satisfaction of these targets [10]. The clearly defined targets derived from the implementation of that law are as follows [11,12]:

- 20% of the gross final energy consumption to be contributed from RES by 2020
- 40% of the total power generation to be provided from RES by the same year (2020)
- a specific share (20%) of heating and cooling load to be met by RES in 2020
- a 10% penetration level of RES in the transportation sector

The Greek government aims at reaching a wind capacity of 7.5 GW in 2020 (currently installed wind capacity amounts to around 1.5 GW) due to its high wind (and solar) potential. In order to fully deploy that potential, a number of islands' interconnection projects have been put into action, namely Cyclades and Crete's interconnection with the mainland power system in 2016 and 2020 correspondingly [12]. As a consequence, an in-depth and rigorous analysis is required to deal with the high variability arising from the integration of rapidly penetrated RES-based electricity into the power grid. These harmful effects can be alleviated through the expansion and/or higher utilization of interconnection capabilities with neighboring countries, and the introduction into the system of more flexible units such as NG and hydropower plants. Flexibility levels, along with long-term economic and environmental benefits, can also be enhanced by making use of storage [13] and demand-side management measures [11,14]. As a result, strategic long-term GEP incorporates many challenges (economic viability, environmental sustainability, and grid's stability) that have to be addressed systematically and simultaneously in the most effective way.

There has been extensive research regarding the GEP problem of the GPS by many researchers employing different modeling tools. Roinioti et al. [15] presented an analysis of the GPS for the period between 2009 and 2030, making use of the LEAP modeling tool. They developed a range of possible scenarios, in terms of Gross Domestic Product (GDP) growth and CO_2 emission allowances price, and examine their effectiveness based on power generation composition, as well as on economic and environmental terms. Their findings suggest a trade-off relationship between capital cost and CO_2 emissions, and that NG play a significant role in all scenarios, in terms of both installed capacity and power generation. A significant decrease in the contribution of lignite in the power generation mix is also highlighted. However, all electricity demand cases are regarded as overestimated reflecting high expectations with regard to GDP growth.

Dagoumas et al. [16] examined the evolution of the GPS up to 2020 by developing several scenarios concerning the implementation of a post-Kyoto target based on WASP IV and BALANCE platforms. In order for this target to be achieved, an increased deployment of both NG and RES is suggested, while the incorporation of supercritical coal units results in additional cost savings. The study highlights also the importance of CO_2 emissions allowance price leading to different expansion paths according to its level.

Rampidis et al. [17] simulated the GPS using the module BALANCE in order to investigate the feasibility and viability of alternative scenarios for the expansion of GPS up to 2020. All possible options are evaluated in terms of economic feasibility, emissions performance and energy safety.

Kalampalikas and Pilavachi [18] studied the GPS for the period 2009–2030 using the modeling tool WASP-IV, on the conditions that RES do not meet EU targets. They concluded that a power mix consisted mainly of NG units is highly beneficial in energy, environmental and cost terms. The same authors studied in another work the same problem under the assumption that RES meet EU targets [19]. Their findings indicate that although the achievement of EU targets can be better implemented with high share of NG units, it leads to higher requirements in installed RES capacity, comprising an extremely capital intensive option. However, the decisions of their approach are based on a large number of assumptions, and key decisions such as optimal capacity expansion, the existence of multiple interconnected regions, etc. are not systematically studied.

Voumvoulakis et al. [20] examined the impact that large scale penetration of RES is going to have in order for the GPS to achieve the 2020 RES targets. For that reason, three scenarios were developed with the use of WASP IV software package, characterized by different type and capacity of interconnections, as well as different pumped storage capacities. One key result of the study is that a significant rise in the system's reserve requirements is expected due to the sporadic nature of the highly penetrated RES. In the absence of new flexible units, the spinning reserves have to be provided from the operation of additional units in the day-ahead scheduling, each of which working at a lower level. From that plan, it is suggested that the objectives of electricity markets' liberalization and decarbonization of power mix may be incompatible and/or contradictory.

Agoris et al. [21] presented an analysis in order for the GPS to achieve the Kyoto targets using the R-MARKAL and WASP IV modeling tools. The results indicate a gradually decreasing utilization rate of lignite units, greater penetration rate of NG and significant investments in RES units.

Since the majority of studies were developed before Greece's deep economic recession, the projection of electricity demand is considered overestimated, as well as some technology options (e.g., coal, oil units) are not included in the country's current energy roadmap.

A profound limitation characterizing the deterministic optimization models is that they cannot capture the uncertainties inherent in some of the parameters of the GEP problem. These typically concern fuel prices evolution, capital cost of new technologies, as well as availability of power units, especially renewables. There are several alternative techniques that can be employed to address these uncertainties such as scenario-based [8] and [22–24] and/or sensitivity analysis [4] and [25,26]. However, these techniques are ineffective in representing the interaction and