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A bottom-up optimization model for the long-term energy planning of the Greek power supply sector integrating mainland and insular electric systems

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ABSTRACT

The energy planning of power sector constitutes a multifaceted challenge for policy makers, incorporating a variety of economic, technological, environmental, political and social aspects in order to ensure the unhindered equilibrium between electricity demand and electricity supply. This paper presents a deterministic bottom-up Mixed Integer Linear Programming model for the long-term energy planning of national power supply systems, having special focus and modeling effort on the peculiar case of Greece. It is a least cost optimization based model being expanded and enhanced with the integration of electric interconnections and the evident participation of environmental dimension. Its superstructure consists of multiple mathematical expressions representing power demand patterns, technical constraints, operation rules, penetration potential of energy sources, economic aspects, technological availability, environmental obligations and other sectoral targets and commitments applying in the electricity supply field. Its main contribution lies on the holistic methodological approach adopted, concerning the discrete electric systems of mainland and insular areas in Greece by proposing a novel way of simulating the potentiality of their submarine interconnection. The present model is applied on a real case study concerning the Greek electricity planning problem for the period 2014–2024, through the elaboration of two alternative evolution scenarios. The underlying objective is multifarious: (a) to deliver the portfolio of new capacity investments, the fuel mix trend, the penetration of renewable energy sources and the progress of achieving country's commitments and targets, and (b) to investigate and highlight the potential economic, energy and environmental benefits arising from the electrical interconnection of Greek islands to the main continental power system.

1. Introduction

Power sector represents the core link of electricity's energy chain and the fundamental pillar of a country's energy system. It comprises all production units and technologies employed to convert and transform primary energy sources (fossil fuels, renewables) through either physical or chemical processes to the final energy form, electricity. The power supply system is the prerequisite module before the transmission system and the distribution networks to deliver electricity to final consumption, energy services and end users.

Over the years, there has been a continuous increase in demand and consumption of electricity which keeps pace with technological, economic and social flourishing in most areas of the world. This rise is mainly driven by the modern and consumerist way of living, the spread use of electricity in services and industry, the enlarged and easier access of much greater population to this crucial commodity as well as due to new power generation and utilization technologies.

The satisfaction of electricity demand proves to be a complicated puzzle as beyond increasing consumption, there are many other intrinsic and extrinsic factors involved that electricity supply industry (ESI) has to take into account. First in order, the severe and escalating environmental problems caused by conventional ways of generating electricity such as greenhouse effect leading to global warming and climate change, acidification phenomena, air and water pollution etc. ESI is one of the largest polluters in local and global level producing enormous quantities of emissions in atmosphere like CO_2, SO_2, NO_x and PM. Other significant issues concern nuclear accidents, intensive land uses, land contamination and erosion, degradation of water reserves due to their use in

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hydroelectric power plants and cooling towers and of course the avowed depletion of fossil fuels supplies. Renewable energy sources (RES) continuously increase their share in power generation mix contributing to the electricity demand satisfaction while at the same time constraining man of the aforementioned environmental problems. But RES and especially wind and solar energy are intermittent energy sources causing inevitably fluctuations in power supply reliability and integrity. Other extrinsic parameters are related to national and international laws and treaties imposing commitments and obligations, sociopolitical status, geomorphological conditions, climate etc.

The dominant intrinsic factor is the final product itself, electricity. In contrast to other commodities, power has to be supplied instantly and automatically to consumers without being permitted and tolerated any delays or deficiencies. Furthermore, electricity via production and distribution technologies cannot be stored in such sufficient quantities (stocks) able to flexibly respond to demand fluctuations. The only large scale exception is hydro-pumped storage power plants followed by medium to small scale hybrid systems and batteries which still have technical, spatial and financial limits. On the other hand any power production surplus combined with disposal failure caused by either (a) unexpected fall in demand, (b) priority changes in power plants' commissioning, (c) excess in RES production or (d) inaccessibility to neighboring electricity markets, implies electricity rejection causing severe economic losses for electric utilities [1]. Last but not least, ESI represents one of the most capital intensive industries as it presupposes very high investment costs for establishing production units characterized by medium to long payback times [2].

ESI operates into a multifaceted framework of economic, technological, environmental, political and social aspects, dealing with a variety of queries to answer, many problems to solve and new coming challenges to respond. Energy planning is the conditio sine qua non to manage and to equilibrate the electricity demand and supply sides as well as to ensure the effective planning and operation of power supply sector itself.

Energy planning can be classified according to the time dimension into short-term, medium-term and long-term. Short-term energy planning corresponds to day ahead scheduling (DAS) concerning the satisfaction of electricity demand on a daily basis. In this paper, the focus stays on long-term energy planning for the power supply sector which often appears with other alternative terminologies like: capacity expansion planning, generation expansion planning, power system planning, power system expansion planning, least cost electricity planning or ESI planning.

The basic concept in power sector's energy planning is the determination of the optimum mix of power generation technologies in order to meet the projected electricity demand in a future period while also satisfying manifold constraints [3]. Capacity expansion planning is occupied with four major queries concerning investment decisions about power installations [2,4–7]:

- What? (the type of technology to choose)
- How? (the number, the size of installed capacity)
- When? (the time to build, operate, retire, the time sequence)
- Where? (the location to install)

The cradle of energy planning lies in satisfying electricity demand by minimizing the total cost of operating and expanding power supply sector. In early capacity expansion planning problems, cost minimization was the single criterion taken into account in the decision process. After 1980s, this traditional consideration was altered, espousing a multicriteria approach caused mostly by the incorporation of the environmental dimension. It was the environmental problems that triggered the international social and political interest to institute new and stricter legislations with specific commitments and penalties for ESI as acknowledgment to its large and diachronic share of responsibility. Environment has been upgraded to a crucial and integral aspect for designing future capacity expansion strategies consolidating the triplet 'Economy, Energy and Environment' (3Es) [7].

The standard practice to realize long-term energy planning is the construction and use of energy models. Energy models correspond to the most prevalent and interesting method to simulate energy systems providing answers for a sustainable expansion and operation of ESI.

Bibliography abounds with electricity planning models being developed from the early 1950s up today, many of which belong to the category of Mixed Integer Linear Programming (MILP) problems. Hobbs [8] presented a simplified least cost MILP model including demand-side management (DSM) in order to satisfy future demand. The model's objective function represents the present value of the total investment and operation cost of power plants, the investment cost of DSM measures and the unserved demand penalties.

Hashim et al. [9] formulated a MILP model with special focus on CO_2 emissions' reduction for the Ontario Power Generation system. The model appears in three alternative versions: (a) the economic mode, having a cost minimization objective function, (b) the environmental mode, minimizing CO_2 emissions, and (c) the hybrid approach, combining both economic and environmental objectives by expressing and internalizing CO_2 emissions cost. Mirzaesmaeeli et al. [10] developed a deterministic multi-period MILP model for the energy planning of Ontario's electricity sector. The model's scope is to determine the optimal mix of energy supply sources and CO_2 mitigation options by minimizing the total discounted present value of all period's cost.

Sharan and Balasubramanian [11] designed a MILP model adopting an integrated approach on dealing with power generation and transmission systems paying special attention on modeling real power flows over transmission lines by considering Kirchhoff's laws. Under this concept the objective is to minimize both capital costs for new power plants and new transmission lines along with the fuel costs deriving from plant operation including fuel transportation expenses. The proposed comprehensive model proves to be more advantageous compared to a sequential and separate approach of first implementing the energy planning of power sector and afterwards this of transmission network.

Chen et al. [12] presented a generation expansion planning MILP model applied to Taiwan's power sector. Chang [13] proposed a multi-period network design MILP model by using scenario-based programming techniques also applied to Taiwan's electrical system, showing that the share of RES in power mix should be increased. The model's objective is to minimize expected value of total levelized costs of power generation and power distribution, in order to answer the questions of which, how and when new generation plants and transmission lines are going to be constructed. Li and Li [14] presented a mixed 0–1 integer linear programming model specially adapted for the power generation expansion of a China's province, facing the problems of acid rain and greenhouse effect. The model focuses on these two severe air pollution problems by incorporating NO_x emission reduction and energy saving targets for the case of coal-fired power plants.

Focusing on studies related to the Greek power system's energy planning, Vlachou et al. [15,16] used WASP III for the period 1995–2025, in order to determine the least cost capacity expansion strategies under the basic prerequisite of reducing CO_2 emissions at a desired level. Study's results showed that the use of lignite to generate electricity can be replaced by natural gas, hydropower plants and RES or even by introducing new lignite-fired or coal-fired power stations with carbon capture and storage technologies.