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MILP model for long-term energy mix planning with consideration of power system reserves

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HIGHLIGHTS

- Individual representation allows for accurate planning of power system expansion.
- Both power and energy balance are considered.
- RES expansion must be followed by increased power reserves margin.
- Application of financial costs provides reliable results.

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ABSTRACT

The purpose of this paper is to present the novel long-term energy mix optimization model *eMix*, which takes into account daily requirements of power system operation (primary, secondary and tertiary reserve) and how should they react to increasing RES penetration.

Until now there has been no computational effective, long-term optimization model of energy mix with individual representation of power generating assets that allows for RES development incorporation and consider the daily requirement of power system operation. Existing unit commitment models, although comprehensive, are not appropriate for long-term, large-scale problems because of computational limitations. The *eMix* links long-term planning (investments) with short-term requirements of power system operation reserves (primary, secondary, tertiary) provided by dispatchable units. Additionally, development of the RES introduces stronger requirements to the reserve's level in order to maintain the flexibility of the power system operation. This relation has significant impact on the final energy mix and was modeled in the *eMix*. The costs are calculated annually for each individual unit (given to the application of Mixed Integer Linear Programming), to reflect the real conditions of energy sector operation, where annual repayment of loans, amortization as well as operation and maintenance costs are applied. *eMix* is also fully scalable and allows for freely definable interval and horizon of the calculation.

To prove the quality of presented model, the authors calibrated it with the data from Polish power system for different scenarios. Results indicate that the consideration of financial costs and required reserves increase the reliability of the optimization outcomes.

1. Introduction

1.1. Research motivation

Energy mix (EM) is a technological structure of electricity generating units in a power system, able to provide power and energy balance. It is mainly determined by the total costs of the electricity generation, but also by technical and economic constraints or political decisions.

Although in most cases, generating units are constructed by private investors, the energy mix planning, as a strategic task, is entrusted to the policy makers and government administration. They possess administrative and legal instruments for controlling EM development. Adequate EM requires a long-term planning and it cannot be frequently modified because of the inertia in the power system investments.

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Traditionally, EM optimization, known also as generation expansion planning (GEP), has aimed at reducing cost of electricity production taking into account an access to the fuel and technical constraints on the power system operation. Increasing environmental concerns lead to the strict energy and climate policies, which are the main stimuli to EM. In October 2014, the European Council agreed to 43% reduction of CO_2 emissions for the period between 2020 and 2030 with the reference to year 2005.

The estimation of the future EM has to take into account the security of electricity supply and power system reliability. The obtained set of power generating units has to meet not only the peak power demand but also fulfill the requirements of the safe operation of the power system in every moment. Thereby, the short-term variability of generation caused by the intermittent RES (wind turbines and PV installations) and daily fluctuations of load requires the backup capacity that will be flexible enough to balance these changes. This requirement is not fully included in existing EM optimization models.

The paper presents the development of useful and reliable methodology for EM optimization taking into account different approach to power generating units, costs and power system reserves. It demonstrates that it is possible to develop bottom-up and long-term model for energy mix optimization, based on representation of individual generation units with annual costs calculation (including financial ones) and daily requirements of power system operation (such as daily, not only annual, and power reserve margin). Despite the complexity of the problem, an adequate modeling allows for preserving computational efficiency of the model [1].

Novel EM optimization method is examined using Polish power sector data. It presents the possible Polish energy mix that would be in accordance with the EU energy policy and provide the sustainable power system development. The model was used by the Polish Ministry of Economy for the preparation of the Energy Policy for Poland until 2050, and was used for analyses made by the National Development Council and presented to the President of the Republic of Poland, describing situation of the power sector in Poland.

1.2. Key contribution

The contribution of research presented is a novel concept of energy mix optimization, which better than existing models reflects reality of the power system and energy sector operation. The presented generation expansion planning tool is based on the MILP and incorporates every single centrally dispatched power generating unit. The required daily power reserves (primary, secondary and tertiary) of individual power units are included in the model, what allows for RES development linked with conventional thermal power plants. Moreover, the model optimizes both: power capacities to cover power balance and electricity generation to cover energy balance within two separated sets of variables. Thus, the model takes into account the limited operation of conventional units that is caused by the overcapacity and the presence of prioritized RES in the power dispatch. This phenomenon increases the overall unit's cost since it does not fully benefit from its availability. It allows considering the impact of decrease of operation time of conventional units on the rise of overall units' costs in the long perspective. Additionally, the costs in the model are calculated annually what allows for the better reflection of the power units' construction costs (including financial costs) and operation costs.

1.3. Paper structure

At the beginning of the paper there is an introduction with key contribution of the novel energy mix optimization model. Subsequently, there are presented recent achievements in Energy System Modeling with thorough review of already existing EM optimization models. Next, the authors presented methodology description with explanation of the need of binary programing in energy mix optimization, model structure and complete description of mathematical formulations in the model. Quality of the model is examined in the next section and results are presented. In the end, after conclusions, there are appendices that help to order the data and understand some of the assumptions made in the article.

2. Recent achievements in energy system modeling

Energy Mix (EM) optimization, called also Generation Expansion Planning (GEP), is a part of wide field of research, named energy system modeling. There are two main approaches for energy system modeling: top-down and bottom-up. The former focuses on the economic issues of the energy system operation, while the latter represents engineering approach and starts from technical aspects and procedures [2–4]. There are several comprehensive and extensive reviews of the energy system modeling. Connolly et al. in [5] created clear unification of the developed models according to the tools applied (simulation, scenario, equilibrium, top-down, bottom-up, operation optimization, investment optimization and combined tools). The more tools are used, the more model is complicated, but on the other hand provides more general solutions. Review mentioned and other [3,6,7] allow for better evaluation of the novel models proposed.

Sometimes the top-down models are identified shortly as energy system models, while bottom-up as power system ones. Combining them is always complex but highly required process. According to [8,9], the need for the soft links between power system models and energy system models are needed due to the appearing gaps between engineering and economic approaches. Until now, there have been many optimization models developed, but according to the authors' best knowledge, none of them allows for long-term GEP optimization taking into account daily requirements of power system operation (primary, secondary and tertiary reserve) and their relation to RES penetration (see Table 1):

As a general rule, EM optimization is a dynamic problem. Therefore, it should apply the dynamic programming (DP). However, due to the complexity, such an approach is limited to small, usually, benchmark systems, in a short-term analysis [12–15], thus they are not applicable. Complexity increases massively extending the model size, what is knows in the literature as "*curse of dimensionality*" [16].

Some researches focused on nonlinearity in optimization models. There were attempts to apply MINLP (Mixed Integer Nonlinear Programming) for energy mix, but pure nonlinear approaches to the GEP can be also found in literature. The commonly used approach to the MINLP is application of the Benders decomposition [19,20]. It allows for transformation of the typical MINLP problem into mixed integer linear programming problem (MILP). This method ensures computational efficiency and guarantees a global solution (while the pure MINLP provides with only local ones) (See Table 2.)

Because the MINLP models are often transformed to the MILP problems to facilitate model solving and to guarantee the local solution, some researchers have started to develop pure MILP model without the need for Benders decomposition application. First MILP models were based on the decision tree method [23]. Nowadays, decision tree is a basis for advanced MILP solvers (see Table 3):

Another group of the MILP energy mix optimization models focus on the uncertainty of the input data and model parameters (see Table 4):