Co-optimized GEP and NEP

Mathematical models

The objectives of electric power **Generation Expansion Planning (GEP)** and **Network Expansion Planning (NEP)** problems are to determine the *"optimal"* selection of generation and network technologies (in a broad sense) and the *right time* and *right place* to construct (*and/or dismiss*) them, while ensuring an 1) economic, 2) reliable, and 3) environmentally acceptable supply according to the predicted demand. Needless to say these problems involve amount of money of the order of magnitude of the tens of billions € for large countries.

A typical GEP optimization model has 1) a planning horizon, 2) an economic (multi)-objective including the present value of the total cost and other components, 3) a long set of constraints including: capacity limitations, environment regulations, fuel costs, customers demands, fuel availability (for instance gas pipelines for CCGT) and mix diversification requirements, and 4) a set of the decision variables representing the operating and expansion options (that depends on the perspective of the actor). To make the matter even more complicate, in the predominant market based models, the GEP and NEP problems must also take into account present, and future, market rules and incentives.
Some author define the GEP and NEP *co-optimization problems* accordingly with the following definition: *co-optimization is the simultaneous identification of two or more classes of investment decisions within one optimization strategy*. If co-optimization is used by a monopolist integrated utility, then its main result is the identification of joint GEP-NEP that are lower in cost than would be if GEP and NEP were developed separately. However, co-optimization can also be used within countries that are market based and where NEP is performed by one entity (TSO) while GEP is performed by others (GenCos). Co-optimization can be naturally be compared to the "*one optimization strategy*" that may consist of a formulation to solve a single optimization problem (e.g., for a GenCo in the GEP perspective, maximize expected profit subject to budget constraints) or it may consist of a formulation to solve an iterative series of optimization problems (i.e., sequential yet possibly coordinated generation and transmission planning).
As an example of goals of a GEP-NEP co-optimization we list the following:

- savings of transmission and generation investment and operating costs
- more efficient decisions concerning generation dismissals and repowering
- more appropriate treatment of intermittent resources
- efficient integration of non-traditional resources such as demand response, customer-owned generation, other distributed resources, and energy storage systems
- fuel mix diversification benefits
- improved assessment of the ramifications of environmental regulation and compliance planning
- reduced risk and attendant effects on resource adequacy and costs.

Historically the practice was to attack the GEP problems first, and then the NEP ones. This approach was motivated because of 1) the complexity of the coupled problem(s), 2) because of the controllability of the traditional power plants with their different technologies (Nuclear, Coal, Steam Turbine, CCGT, Gas Turbine, Hydro Basin), 3) because interregional power exchanges were limited. However assessing both simultaneously to provide an integrated plan is capable of identifying attractive solutions that may not otherwise be considered. Doing so it is becoming more important, due to 1) the increasing penetration of non programmable renewable resources, energy storage systems, distributed generation and demand response and 2) the need for interregional energy transfers to take advantage of diverse and remote sources of power. For instance, it can be argued that the newly launched Price Coupling of Regions (PCR) in EU does not only enable to clear at European level the Day Ahead Markets in the short term, but also gives the opportunity to consider at regional level the GEP-NEP problems in the longer terms. Thus, NEP are *n ot* necessarily the least-cost means of meeting those needs (considering both economic and environmental costs). Second, siting of new generation, including renewable sources, is influenced by the availability of transmission, so that different transmission expansion plans will ultimately result in different patterns and even mixes of generation investments.

In what follows we will consider the GEP and NEP as a single unified problem, and discuss recent approaches for it.

Modeling and algorithmic considerations

First of all, we note that co-optimized GEP and NEP problems posed significant computational challenges. Computer resources available to planners before, say, ten years ago were incapable of supporting the solutions of co-optimization models. Fortunately, recent advances in computation methods have provided satisfactory solutions to co-optimized GEP and NEP problems with reasonable computation times, so now realizing savings by using co-optimization is a real possibility. Also we observe that in GEP-NEP optimization problems uncertainty is, of course, ubiquitous.

There are several challenging issues in the co-optimization of GEP and NEP. First, conflicting objectives: GEP can be driven by prices but the same principle may not apply to the NEP (eg. 1). Second, power system constraints such as network flow limits, load demands, and reliability requirements link the two planning problems, which introduce an additional dimension of difficulty in finding feasible and practical planning solutions. Third, one of the main obligations of expansion planners is to facilitate a fair and competitive market. The planner also has to take into account uncertainties associated with renewable energy, non-traditional generation resources such as microgrids, fuel costs, component outages (such as transmission lines, plants, and transformers), and customer behavior including demand response. The co-optimization of GEP and TEP becomes much more challenging when contemplating the full range of uncertainties relevant to expansion planning. Earlier attempts uses Benders decomposition-based approach developed to separate and coordinate the investment problem and operating subproblems (e.g. [2]). Reliability issues were assessed in terms of customer interruption functions in co-optimization models [3], allowing tradeoffs between outage, investment, and operating costs. However, these earlier models were oversimplified and thus deemed impractical for market-based generation and transmission expansion planning.

In general, co-optimization is viewed as a bi or tri-level optimization problem for generation and transmission and iterative schemes have been used to coordinate the two planning problems. As an example, Baringo and Conejo [4] presented a bi-level stochastic co-optimization model and transformed it into a single-level mathematical programming with equilibrium constraints.The author show - as expected - that transmission expansion decisions significantly affect wind power capacity expansion even though investment cost in transmission expansion is much lower than that in wind power capacity. A recent study in [5] presented a co-optimization model that incorporated transmission congestion costs. It was shown that distributed generation could mitigate congestion and defer transmission investments. A follow-up study in [6] proposed a co-optimization model which accounted for incentives offered to independent power producers (IPP).

As for data uncertainty, stochastic programming was applied in [7], [14] to simulate random outages of system components. It was shown that even simple co-optimization models could result in significant savings when optimizing transmission and generation assets. Also stochastic programming was the main ingredients in order to consider alternative scenarios of future economic, regulatory, and technology developments.

GEP and NEP co-optimization models include both transmission expansion planning and generation planning for multiple years/decades and multiple locations/regions. This leads to computational challenges due to the fact that the details of power systems can greatly increase the size of the problem. In addition, nonlinearity and integer variables and uncertainties can add additional complications. As discussed in the Operational-Network section, modeling of transmission flows by itself can be a very difficult non-linear program (the OPF with full AC representation). After adding investment expansion decisions, the problem becomes an even harder mixed-integer nonlinear program.

Several simplifications are therefore applied, such as:

Simplification approaches include:

- Aggregation of input data and model variables (e.g., [9])
- Simplification of dynamics and uncertainties (e.g., [9])

Approaches to modeling aggregation include:

- Location aggregation (e.g., aggregated region(s) instead of exact locations)
- Time period aggregation (e.g., multiple year instead of daily data) (e.g., [10])

However even if model aggregations and simplifications are effective for reducing computational complexity, models then lose fidelity and accuracy to some extent. Thus, it is desirable to solve large-scale and complicated problems. At the present time we have probably two approaches, 1) try to linearize everything by means of the many possible approaches eventually resorting to piecewise linear modeling, or 2) using decomposition approaches such as those well known in the optimization community, say: Benders Decomposition, Column Generation and Branch-and-Price. Today, there is a very extensive research on the topic, mainly for stochastic models, see the references listed in the section.

References:

[1] J. H. Roh, M. Shahidehpour, and Y. Fu, “Market-based coordination of transmission and generation capacity planning,” IEEE Transactions on Power Systems, Vol. 22(4), 1406–1419, Nov. 2007

[2] M. Pereira, L. Pinto, S. Cunha, and G. Oliveira, “A decomposition approach to automated generation/transmission expansion planning,” IEEE Transactions on Power Apparatus and Systems, Vol. 104(11), 3074–3083, 1985

[3] W. Li. and R. Billinton, “A minimum cost assessment method for composite generation and transmission system expansion planning,” IEEE Transactions on Power Systems, Vol. 8(2): 628–635, 1993

[4] L. Baringo and A. J. Conejo, “Transmission and Wind Power Investment,” IEEE Transactions on Power Systems, Vol. 27 (2): 885-893, 2012

[5] M. Shahidehpour, “Investing in expansion: The many issues that cloud electricity planning,” IEEE Power and Energy Magazine, 14-18, Jan 2004

[6] M. Shahidehpour, “Global broadcast - transmission planning in restructured systems,” IEEE Power and Energy Magazine., Vol. 5(5), 18-20, Sep./Oct. 2007

[7] J. A. López, K. Ponnambalam, and V. H. Quintana, “Generation and transmission expansion under risk using stochastic programming,” IEEE Transactions on Power Systems, Vol. 22(3), 1369–1378, Aug. 2007

[8] A. H. van der Weijde and B. F. Hobbs, “The economics of planning electricity transmission to accommodate renewables: Using two-stage optimisation to evaluate flexibility and the cost of disregarding uncertainty,” Energy Economics, Vol. 34(5), 2089-2101, Sept. 2012

[9] Y. Scholz, Renewable Energy Based Electricity Supply At Low Costs – Development Of The Remix Model And Application For Europe, PhD Dissertation, German Aerospace Center (DLR), Institute of Technical Thermodynamics, 2012

[10] M. Shahidehpour, W. Tinney, and Y. Fu, “Impact of security on power system operation,” IEEE Proceedings, Vol. 93(11), 2013 – 2025, Nov. 2005

[11] G. Latorre, R. D. Cruz, J. M. Areiza and A. Villegas, "Classification of publications and models on transmission expansion planning," *IEEE Transactions on Power Systems,* vol. 18, pp. 938-946, 2003.

[12] R. Hemmati, R. Hooshmand, A. Khodabakhshian, "Comprehensive review of gen-eration and transmission expansion planning", IET Generation Transmission Distribution 7(2013) 955–964.

[13] S. Lumbreras, A. Ramos "The new challenges to transmission expansion planning. Survey of recent practice and literature review," Electric Power Systems Research 134: 19-29, May 2016 10.1016/j.epsr.2015.10.013

[14] L.G. Escudero, A. Alonso-Ayuso and F.J. Martin-Campo, On a strategic multistage scenario tree framework with tactical multi-period two-stage trees for electricity network capacity expansion planning under uncertainty, http://www.energy-workshop.cz/pdf-wednesday/escudero.pdf, 2017

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