INTEGRATED RESOURCE AND RESILIENCE PLANNING FOR POWER SYSTEMS: A NON-PROBABILISTIC APPROACH TO ADDRESS DISRUPTIVE EVENTS

Fernanda S. Thomé
fernanda@psr-inc.com
PSR
Praia de Botafogo, 370, 1st floor

Luiz Carlos da Costa Jr
luizcarlos@psr-inc.com
PSR
Praia de Botafogo, 370, 1st floor

Mario V. F. Pereira
mario@psr-inc.com
PSR
Praia de Botafogo, 370, 1st floor

ABSTRACT

The pursuit of efficiency in productive sectors has exposed vulnerabilities to disruptive events, necessitating a shift towards resilience strategies. In the energy sector, the impacts of climate change and recent global events have intensified the need for energy resilience. Expansion planning models traditionally minimize costs by considering probabilistic models for uncertainties. However, these models fail to capture extreme events adequately. This work presents an expansion planning approach incorporating resilience measures. The methodology involves analyzing critical scenarios, such as severe droughts or significant reductions in wind production, and solving deterministic operating models for each scenario. A case study with Costa Rica demonstrates the impact of resilience on the generation mix and operative marginal costs. The results emphasize the importance of source diversification and show that incorporating resilience measures can mitigate the severity of extreme events and ensure supply continuity.

KEYWORDS. Resilience. Power system expansion planning. Benders decomposition.

Paper topics: OR in Energy, Oil and Gas. Mathematical Programming.

http://live-proceedings.pantheonsite.io/p/175151

1. Introduction

The last few years were marked by an incessant search for efficiency in all productive sectors. However, recent events, such as Ukraine war and the pandemic, conclusively showed that ultra-efficiency had made production and logistics chains extremely vulnerable to disruptive events. This has led to a radical change in the companies' strategies [Tett, 2022], where the emphasis is now on resilience, that is, the ability to reduce disruptions and quickly recover after a very severe event. The resilience incorporation in the energy area was already a topic of great interest and urgency due to the acceleration of climate change impacts, which has been causing extreme droughts and floods and also record temperature increases in several parts of the world.

The concern about the occurence of these events has brought a new mindset in the expansion planning towards energy resilience strategies: (i) Work with extreme scenarios, without assigning a specific probability; (ii) Diversify the supply sources geographically and by technology; and (iii) Create redundancies and storage, such as the use of FACTs, batteries and reversible plants.

2. Basic formulation of expansion planning

Expansion planning models determine the reinforcement schedule of generation and interconnections that meet the expected future demand in the most economical way. These models minimize the net present value of the sum of investment costs in new equipment, plus the expected value of the operating cost of the system, basically associated with the fuel used by plants. The optimal solution of this problem is quite complex both in methodological terms and in computational effort, as it requires binary decision variables (whether to build or not each candidate equipment at each stage) to represent the investment costs; and probabilistic simulations of the system operation [Pereira e Pinto, 1991] for several inflow and renewable generation scenarios to estimate the expected value of operating costs resulting from a given candidate expansion plan.

In general terms, this problem is given by the following formulation, where x is the investment decision variable of building generation projects, g and d are the operation decisions in generation and deficit. I is the investment cost, c and c_d are the generation and deficit costs, $\bar{g}$ is the generation capacity and D is the energy demand.

$$\begin{aligned} Min \quad & I \cdot x + c \cdot g + c_d \cdot d \\ s.t. \quad & g + d = D \\ & g - \bar{g} \cdot x \leq 0 \\ & x \in \{0, 1\} \end{aligned}$$

The complexity involved in solving this problem for real systems requires the use of decomposition technique such as the Benders decomposition approach [Gorenstin et al., 1993]. This methodology iteratively solves an investment and an operation modules independently, as shown:

Investment

$$\begin{aligned} Min \quad & I \cdot x + \alpha \\ s.t. \quad & \alpha \geq w(x^k) - \pi^k \cdot \bar{g} \cdot (x - x^k), \forall k \in K \\ & x \in \{0, 1\} \end{aligned}$$

Operation

$$\begin{aligned} w(x^k) = Min \quad & c \cdot g + c_d \cdot d \\ s.t. \quad & g + d = D \\ & g \leq \bar{g} \cdot x^k \quad (\pi^k) \end{aligned}$$

At each iteration k, an expansion plan x^k is obtained from the investment problem and informed to the operation problem. The solution of this problem $w(x^k)$ and its sensitivity factors, or dual variables, π^k, are used to build Benders cuts, which correspond to an approximation α of

the operation cost function that are incorporated back to the investment problem. This way, the algorithm gradually improves the expansion plan until optimality.

The modularization of the expansion problem is specially important to allow the use of the most appropriate algorithm for each part of the problem. Besides, it allows the model to represent additional planning attributes, such as reliability, flexibility and, as presented next, resilience.

3. Expansion planning with resilience

Traditionally, expansion planning problems use probabilistic models to represent the various sources of uncertainty and variability, however, they are suitable only when the variations are relatively small. The reasons these models have low adherence to severe events are: (i) it is extremely difficult to know which is the most suitable distribution for extreme events; (ii) as, by definition, these events are very rare, the parameter estimation is extremely uncertain; and (iii) a small error in this estimation can lead to dramatically big mismatches.

For these reasons, planners should start analysing "what-if" scenarios that were previously discarded because the probabilistic models considered them "impossible". The incorporation of the resilience module into the expansion planning problem is given by the definition of critical scenarios, for example: the occurrence of a severe drought; or a drastic reduction in wind production; or the interruption of all LNG imports; and so on. For each scenario, a deterministic operating model is solved in order to ensure supply over a specified period for the duration of these events.

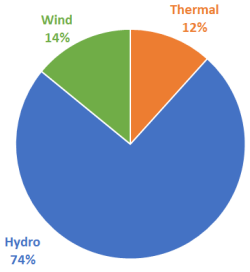
$$
\begin{aligned}
&\underline{\text{Resilience}} \\
r_s(x^k) = Min \quad & d \\
s.t. \quad & g + d = D \\
& g \leq \bar{g} \cdot \sigma_s \cdot x^k \quad (\pi_s^k)
\end{aligned}
$$

where σ_s is the reduction factor that models scenario s of a severe event over the generation capacity. The solution of this problem generates a feasibility cut for the investment problem given by the following contraint, which helps the model to seek for a resilient expansion plan:

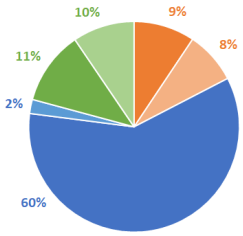
$$r_s(x^k) - \bar{g} \cdot \sigma_i \cdot \pi_s^k \cdot (x - x^k) \leq 0, \quad \forall k \in K, s \in S.$$

4. Case study with Costa Rica

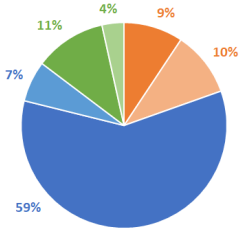
Costa Rica's existing generation mix in 2021 was 74% hydro, 14% wind, and 12% thermal. 109 new generation projects from different energy sources were considered. The model was run twice, with and without the resilience module. One artificial extreme scenario was considered to highlight the effect of the resilience module: a huge reduction of wind generation for one year.



(a) 2021 generation mix



(b) 2035 without resilience



(c) 2035 with resilience

Figura 1: Costa Rica's generation mix

Figure 1 shows that in a purely economic expansion (without resilience) the preferred source was wind power. Given that the extreme scenario was precisely wind generation outage, expansion with resilience diversified sources, investing more in hydro and thermoelectric plants. Although this case is purely illustrative, one of the main drivers for source diversification is resilience, not their synergy, or complementarity, as often argued. The reason is that if a certain source was significantly cheaper than the others, the result of purely economic expansion models will be to use 100% of them. In other words, the diversification of sources is not a priori justified; it must result from an optimization process.

Another interesting result is the impact of the extreme event on operative marginal costs. Figure 2a shows the expected value of OMCs for expansions with and without resilience for the inflow and renewable generation scenarios produced by the stochastic model. These scenarios obviously do not include the extreme wind reduction event. In this case the OMCs are similar, that is, the plan with resilience did not affect the "routine" operation of the system. In turn, figure 2b shows the operative simulation for the extreme scenario. In this case, the difference is very large: the system without resilience basically collapses, while the system with resilience goes through the crisis, with a significant but not catastrophic increase in costs.



(a) OMC without critical scenario

(b) OMC with critical scenario

Figura 2: Costa Rica's marginal costs

5. Conclusions

The pandemic and the Ukraine war recently showed that the current big challenge is to represent extreme phenomena, whose probability is very difficult, or even impossible, to estimate: climate change; geopolitical problems; cyber-attacks and others. The objective is to make the system more resilient, that is, capable of mitigating the severity of the impact of these extreme events and accelerating the recovery of normal operating conditions.

As illustrated by the methodology, resilience measures typically include source diversification, storage distribution and greater self-sufficiency in the system, in order to ensure supply continuity assuming each scenario's occurrence. A very relevant aspect about the presented model is that the decomposition methodology accommodates resilience, which allows representing both probabilistic and extreme aspects in an integrated manner.

Referências

Gorenstin, B. G., Campodonico, N. M., e Costa, J. P. (1993). Power system expansion planning under uncertainty. *IEEE Transactions on Power Systems*, 8:129–136.

Pereira, M. V. e Pinto, L. M. (1991). Multi-stage stochastic optimization applied to energy planning. *Mathematical Programming*, 52(1-3):359–375.

Tett, G. (2022). Supply chain crises force corporate america into a what-if mindset. Finantial Times.