Power System Planning: An Integrated Techno-Economic and Portfolio Approach

Planejamento Energético: Uma Abordagem Integrada Tecno-Económico e de Portfólio

Ian Michael Trotter
Departamento de Economia Rural, Universidade Federal de Viçosa
ian.trotter@ufv.br

Angelo Durigon
Departamento de Economia Rural, Universidade Federal de Viçosa
angelo.durigon@ufv.br

Grupo de Trabalho (GT): GT4. Questão ambiental, agroecologia e sustentabilidade

Abstract
The access to an efficient, affordable and reliable supply of energy is important for both development and the environment. However, many energy planning models focus exclusively on minimizing cost, whilst the studies that have actually considered the trade-offs between cost and risk have suffered from unrealistically simple cost assumptions. Therefore, we present a power system planning approach that integrates a detailed techno-economic energy planning model into a portfolio framework. The techno-economic model features a detailed and realistic representation of the actual cost formation mechanisms of the industry. By integrating the techno-economic model into a portfolio optimization framework, however, we can identify efficient trade-offs between cost and risk, whilst at the same time maintaining a realistic and detailed representation of the power sector. Furthermore, the approach is computationally efficient. As such, the integrated approach will provide realistic system expansion alternatives with efficient trade-offs between cost and risk.
Key words: Energy planning, Power system model, Portfolio theory

Resumo
A aquisição de energia de fontes seguras e eficientes é essencial para o desenvolvimento e para o meio ambiente. Entretanto, a maioria dos modelos de planejamento energético utiliza uma abordagem de apenas minimizar os custos da produção energética, enquanto os poucos que consideraram o trade-off entre custo e risco assumiram custos irreais para a produção de energia. Portanto, este trabalho se propõe a utilizar um modelo tecno-econômico que representa a produção de energia de forma detalhada, integrando-o a uma estrutura de otimização de portfólios. Com isso, é possível identificar relações eficientes entre risco e custo enquanto mantêm um modelo realista e detalhado dos custos de produção do setor de energia. Essa abordagem integrada é computacionalmente eficiente e permitirá modelos mais realistas da produção de energia.
Palavras-chave*: Energia, Planejamento Energético, Modelo Computacional, Teoria do Portfólio*

1. Introduction

The United Nations Sustainable Development Goals aim to "ensure access to affordable, reliable, sustainable and modern energy for all" (UNITED NATIONS, 2015). This highlights the importance of energy, both for development and for the environment. This goal also presents a challenge for the energy sector, who must identify and pursue appropriate trade-offs between these conflicting properties – affordability, reliability, and sustainability.

The majority of existing techno-economic energy planning models feature a detailed representation of the cost structure of the energy system in one or more regions, and focus primarily on identifying the investment and operational decisions that only minimize the expected costs (FODSTAD et al., 2022). Some pioneering studies have applied portfolio theory to power system planning, further exploring the probability distribution of the cost (AWERBUCH; BERGER, 2003; SZOLGAYOVÁ et al., 2012; LOSEKANN et al., 2013; JUÁREZ-LUNA, 2020; CASTRO et al., 2021). This novel approach has provided interesting insights, but the cost-minimization approach has remained dominant because existing studies using portfolio theory have relied on greatly simplified assumptions about the cost structure of the industry, for instance that costs can be represented by a linear combination of installed power generation capacities. The actual costs of power production are determined, in large part, by operational and investment decisions, which have been captured more realistically and in greater detail by the cost-minimization approaches.

In this study, we develop a power system planning approach that incorporates a detailed techno-economic power planning model into a portfolio theory framework. Our approach simulates operational decisions using a standard techno-economic energy planning model that allows a detailed representation of the technological constraints and the industry cost structure, whereas generation capacities are chosen so as to minimize a risk measure applied to the total cost, allowing us to account for randomness in any of the inputs to the techno-economic model. Our approach combines the main strengths of the two frameworks: the techno-economic model provides an accurate representation of the industry cost structure, and the portfolio optimization component provides a more robust and comprehensive objective than pure cost minimization. Our approach will therefore contribute to improved power system planning by identifying possible system development paths that adequately balance cost and risk.

2. An Integrated Techno-Economic and Portfolio Approach to Power System Planning

We now show how an operational techno-economic power system planning approach can be integrated into a portfolio framework for power system capacity planning. The techno-economic model recreates the cost formation process of the power system by simulating detailed operational decisions. The portfolio framework ensures that installed capacities are chosen to optimize a risk measure over the costs. Specifically, we incorporate an economic dispatch model of power system operations (CONEJO; BARINGO, 2017) into the minimization of the conditional value-at-risk (ROCKAFELLAR; URYASEV, 2000).

The conditional value-at-risk can be minimized by way of the convex sample-based auxiliary function introduced by Rockafellar and Uryasev (2000):

$$\min_{\vec{x},\alpha} \quad \alpha + \frac{1}{q(1-\beta)} \sum_{i=1}^{q} [f(\vec{x}, \vec{y}_i) - \alpha]^+$$

in which β denotes a risk level, $\vec{x}$ represents the installed power generation capacities and $\vec{y}$ represents the random variables, with q samples $\vec{y}_1, \vec{y}_2, \ldots, \vec{y}_q$. That is, the method makes no assumptions about the probability distribution of the random variables y – but requires q samples from the distribution. The function $f(\vec{x}, \vec{y})$ represents the costs, conditioned on the installed capacities x and a given realization of the random variables $\vec{y}_i$.

Given installed capacities $\vec{x}$ and a realization of the random variables $\vec{y}_i$, we calculate system costs by accounting for fixed costs $C^F(\vec{x})$ of the installed generation capacities, and simulating power system operations to obtain the operational costs $C^{OP}(\vec{x}, \vec{y})$:

$$f(\vec{x}, \vec{y}) = C^F(\vec{x}) + C^{OP}(\vec{x}, \vec{y}).$$

We construct a deterministic hydrothermal dispatch model to simulate the operation of the power system. The model selects the hourly generation level for the dispatchable generators that minimizes the operational costs over a given time horizon.

Specifically, a hydrothermal dispatch model used in this study defines a set of time periods $\mathcal{T}$, numbered $t = 0, \ldots, T-1$, and a set of dispatchable thermal power generators $\mathcal{G}$. The marginal generation cost (c_g) for each thermal generator $g \in \mathcal{G}$ is linear, such that $c_g L_{t,g}$ represents the cost of the power source g producing the amount $L_{t,g}$ during time period t. The generation level of each thermal generator must be within the minimum and maximum generation levels, $\underline{L}_g$ and $\overline{L}_g$, for each $g \in \mathcal{G}$. Further, assume an equivalent hydro-electric power generator H, with minimum and maximum reservoir levels $\underline{H}$ and $\overline{H}$, initial and final reservoir levels given as $\overline{H}_0$ and $\overline{H}_T$, the reservoir level at the start of each time period represented by H_t, the reservoir inflow during each period given by I_t, minimum and maximum generation levels for the hydro-electric generator given by $\underline{L}_h$ and $\overline{L}_h$, and the actual hydropower generation in a period represented by $L_{t,t}$. Furthermore, wind and solar power generation (which re not dispatchable) are given by $L_{t,w}$ and $L_{t,s}$, whereas the power demand is given by D_t. The following constrained linear optimization problem selects the generation level of all dispatchable power sources in order to minimize the operational cost over the time horizon:

$$\min_{\{L_{t,h}\}_{t\in\mathcal{T}} \cup \{L_{t,g}\}_{(t,g)\in\mathcal{T}\times\mathcal{G}}} \sum_{t\in\mathcal{T}} \sum_{g\in\mathcal{G}} c_g L_{t,g}$$

subject to the following constraints:

$$L_{t,h} + L_{t,w} + L_{t,s} + \sum_{g\in\mathcal{G}} L_{t,g} = D_t, \quad \forall t \in \mathcal{T}$$
$$H_{t+1} = H_t + I_t - L_{t,h}, \quad \forall t \in \mathcal{T}$$
$$H_0 = \overline{H}_0, H_T = \overline{H}_T$$
$$H_t \leq \overline{H}, H_t \geq \underline{H}, L_{t,h} \leq \overline{L}_h, L_{t,h} \geq \underline{L}_h, \quad \forall t \in \mathcal{T}$$
$$L_{t,g} \leq \overline{L}_g, L_{t,g} \geq \underline{L}_g, \quad \forall (t,g) \in \mathcal{T} \times \mathcal{G}$$

The objective function requires the minimization of the operational costs. The first constraint is known as the power balance equation, requiring that total power generation equals total power demand. The second constraint represents the transition function for the hydropower reservoir levels, whereas the fourth constraint binds the initial and final reservoir levels, the fifth constraint ensures that the hydro reservoir levels and generation stay within the minimum and maximum level, and the final constraint ensures that thermal power generation remains within the minimum and maximum levels.

The fixed costs of the installed generation capacity can be estimated easily using information from a number of different sources. The operational costs are obtained by simulating the hydrothermal dispatch model, defining the minimum and maximum generation capacities using $\vec{x}$, and with marginal costs, power demand, reservoir inflow and non-dispatchable power generation based on $\vec{y}$. Thus, the cost function $f(\vec{x}, \vec{y})$ will be well-defined, and can be used for finding the portfolio $\vec{x}$ of installed power generation capacities that minimize the conditional value-at-risk. Furthermore, the computational efficiency of the proposed approach is considerable: the hydrothermal dispatch model is formulated as a linear programming problem, and the minimization of the conditional value-at-risk through the auxiliary function has been shown to be a convex optimization problem – both of which can be solved efficiently with standard methods.

We have thereby shown how a techno-economic power system planning approach may be integrated into a portfolio framework, which can be used for capacity planning in a way that accurately reflects the actual cost structure of the industry. This is important in order to better understand the trade-off between power system cost and risk, in order to design power systems that are more affordable, robust and reliable.

3. Final Remarks

We have presented an integrated techno-economic and portfolio approach to power system planning. Compared to existing techno-economic power system planning models, our approach advances by minimizing a risk measure defined over the cost, rather than the cost itself. This provides a more attractive trade-off between cost and risk, which is the main advantage of applying a portfolio approach. Compared to the existing literature that has applied portfolio theory to power system planning, our approach contributes by including a more realistic representation of the industry cost structure, improving the practical applicability of the results compared to existing portfolio approaches. As such, our integrated approach combines the main strengths of the techno-economic and portfolio approaches to overcome several limitations of prior power system planning approaches.

This approach is currently being implemented, and will ultimately be used to perform numerical experiments on the Brazilian power system, and is expected to provide insights into realistic system expansion alternatives with efficient trade-offs between cost and risk.

Furthermore, we believe that the structure of this approach is sufficiently general that it can be adapted to many other sectors, in order identify an efficient balance between cost and risk in a way that respects technological and economic constraints, while realistically representing the cost structure of each sector in a detailed manner.

Acknowledgements

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) Finance Code 001. Ian Trotter would also like to thank Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for financial support (grant number APQ-00993-17).

References

AWERBUCH, S.; BERGER, M. Applying Portfolio Theory to EU Electricity Planning and Policy Making. Paris, France, Feb. 2003.

CASTRO, G. M. et al. Improvements to Modern Portfolio Theory Based Models Applied to Electricity Systems. [S.l.]: arXiv, May 2021. arXiv: arXiv:2105.08182.

CONEJO, A. J.; BARINGO, L. Power System Operations. New York, NY: Springer Science+Business Media, 2017. ISBN 978-3-319-69406-1.

FODSTAD, M. et al. Next Frontiers in Energy System Modelling: A Review on Challenges and the State of the Art. Renewable and Sustainable Energy Reviews, v. 160, p. 112246, May 2022. ISSN 13640321. DOI: 10.1016/j.rser.2022.112246.

JUÁREZ-LUNA, D. Power Generation Portfolios: A Parametric Formulation of the Efficient Frontier. Revista Mexicana de Economía y Finanzas, v. 16, n. 1, p. 1–29, Oct. 2020. ISSN 16655346, 24486795. DOI: 10.21919/remef.v16i1.447.

LOSEKANN, L. et al. Efficient Power Generating Portfolio in Brazil: Conciliating Cost, Emissions and Risk. Energy Policy, v. 62, p. 301–314, Nov. 2013. ISSN 03014215. DOI: 10.1016/j.enpol.2013.07.049.

ROCKAFELLAR, R. T.; URYASEV, S. Optimization of Conditional Value-at-Risk. The Journal of Risk, v. 2, n. 3, p. 21–41, 2000. ISSN 14651211. DOI: 10.21314/JOR.2000.038.

SZOLGAYOVÁ, J. et al. Robust Energy Portfolios Under Climate Policy and Socioeconomic Uncertainty. Environmental Modeling & Assessment, v. 17, n. 1-2, p. 39–49, Apr. 2012. ISSN 1420-2026, 1573-2967. DOI:10.1007/s10666-011-9274-2.

UNITED NATIONS. Transforming Our World: The 2030 Agenda for Sustainable Development. [S.l.], 2015.