Optimal Planning of Electric Power Systems

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Abstract Electric power systems provide an essential service to any modern society. They are inherently large- scale dynamic systems with a high degree of spatio-temporal complexity. Their reliability and security of supply are central considerations in any regional or global energy-related policy. Methods for power systems planning have typically ensured key operational reliability aspects under normal operating conditions and in response to anticipated demand variability, uncertainty and supply disruptions, e.g. due to errors in load forecasts and to unexpected generation units outages. Solutions have been commonly built on capacity adequacy and operating reserves requirements, among others. However, recent objectives for environmental sustainability and the threats of climate change are challenging the reliability requirements of power systems in various new ways and necessitate adapted planning methods.

The present chapter describes some of the issues related to the development of the integrated techno-economic modeling and robust optimization framework that is needed today for power systems planning adapted. Such planning framework should cope with the new context by addressing the challenges associated with the sustainability targets of future power systems, and most notably ensuring operational flexibility against the variability of renewable energy sources, ensuring resilience against extreme weather events and ensuring robustness against the uncertainties inherent in both the electric power supply and system load.

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This chapter presents the context by summarizing the main sustainability drivers for the current (and future) power systems planning and operation. These well-known sustainability targets have become a worldwide imperative in all sectors of economic activity, and are embedded within almost any regulatory or policy dialogue. We will, then, review the particular transformation undergoing in the electric power sector planning, not only driven by the sustainability goals, but also by the more general technological and/or regulatory advancements. The main power systems planning related challenges are detailed, along with a thorough review of previous research works and research gaps. Then, key research questions and ensuing objectives are formulated.

1 Sustainability of Future Electric Power Systems

The electric power industry is at the same time a major contributor to climate change and a sector that will be deeply disturbed by the effects of climate change. The role of the power sector towards climate change stems from the fact that it is the largest contributor to global greenhouse gas (GHG) emissions. From 2000 to 2010, the increase in the power sector emissions outpaced the increase in overall emissions by around 1% per year [1]. In 2018, global energy-related CO_2 emissions rose 1.7% to a historic high of 33.1 Gt CO_2. The power sector accounted for nearly two-thirds of this emissions growth [2]. To reduce emissions to levels equivalent with the internationally agreed goal of keeping the temperature increase below 2 °C of that of pre-industrial levels, the share of low-carbon electricity generation will need to triple or quadruple by 2050 [2].

At the same time, it is expected that over the coming decades the power sector will be significantly disturbed by climate change impacts. For example, power plants, especially those in coastal areas, will be affected by extreme weather events and rising sea levels. Electricity grids will be impacted by storms, and the rise in global temperature may affect electricity generation including thermal and hydro-electric stations in many locations. And while the industry may have options for adapting to climatic changes, significant costs are likely to be incurred [3]. Several actions are, therefore, urgently needed if the reliability and sustainability targets for the power sector are to be achieved.

1.1 Greenhouse Gas Emissions

Controlling GHG emissions ultimately requires "de-carbonizing" the power sector, both by reducing the high demand for energy and by supplying power that generates much less GHG. A clear path for de-carbonizing power production is through what the Intergovernmental Panel on Climate Change (IPCC) describes as a fundamental shift in global investment from fossil fuel to renewable energy [1]. Renewable energy sources have significant potential for reducing GHG emissions and are becoming mainstream investment choices as they are becoming more competitive. In 2012, they accounted for just over half of the new electricity-generating capacity investments globally, while electricity generation from renewable sources increased by over 7% in 2018 alone [2]. Yet only a small fraction of renewable potential has been exploited so far; estimates suggest that in different regions of the world, renewable energy sources can produce more than 2.6 times the energy demand [1]. Another path for supporting the reduction of GHG is placing more stringent limits on carbon emissions for existing or new thermal plants. A clear example is the use of carbon capture and storage (CCS) technology already imposed in many regions.

1.2 Climate Change

Ensuring the resilience of the power system against the adverse effects of climate change is another key element for ensuring the sustainability and reliability of power supply. The past decade has seen a rising frequency in weather-related natural disasters. Damage and loss associated with these extreme events resulted in millions of victims and billions of dollars in losses. There are various ways in which climate change affects the power sector [4]:

- Extreme weather events such as storms, floods and extreme temperatures can impact the power production and delivery, causing supply disruptions and infrastructure damage.
- The reduction in water availability can constrain hydropower as well as the operation of the thermal power plants (fossil fuel and nuclear), which require water for cooling.
- Unusual seasonal temperatures can impact the electricity demand patterns due to the increased need for cooling during summer heat waves, or the increased demand for heating in excessively cold winters.

Although thermal power plants are designed to operate under diverse climatic conditions, they will be particularly affected by the decreasing efficiency of thermal conversion as a result of rising ambient temperatures. In addition, in many regions, decreasing volumes of water available for cooling and increasing water temperatures could lead to reduced power operations, operations at reduced capacity or even temporary shutdowns [5]. The rising temperatures also create challenges for meeting river temperature regulations. For example, in 2009, the French power system at one time lost one third of its nuclear capacity, to respect thermal discharge limits [4].

Within this context, it is clear that current power system planning efforts must be able to account for these future challenges or, otherwise, they run the risk of leading to inadequate and unreliable investments.

2 Electric Power Systems Planning

Power system planning is an important techno-economic problem, which has been addressed extensively both by the sector stakeholders and by academics. Research on power system planning is carried out by governments and power system operators for future system-wide expansion, and for deciding on optimal policies and regulations. It is also carried out within privately owned power utilities in countries which have liberalized the energy sector, to plan for future investments.

Electric power systems planning can be divided into two main problems: generation expansion planning (GEP) and network expansion planning (NEP). Both are typically formulated as optimization problems, seeking to determine the optimal technology mix, location and construction time of new generation units, as well as the optimal size and location of the power lines. Albeit being highly intertwined, the complexity and scale of each problem has led research work to often focus on addressing each of them separately [6].

The present work focuses on the modeling of the GEP problem and the optimization of its solution, as it is considered most critically affected by the future context, both from the economic (costs) and technical (service provision) aspects. In literature, GEP modeling in a centralized planning context can be traced back to the seminal paper [7]. With the power sector being constantly subjected to changes driven by economical, technical, technological and environmental issues, the body of GEP literature has persistently expanded to accommodate the new requirements, through a variety of modeling and solution methods. Some of the developments include: improvements in the details considered, such as reserve requirements [8, 9], reliability and maintenance [8, 10–12], policy developments such as the restructuring of the power sector and the introduction of competition [10, 13–15], CO_2 mitigation solutions [16, 17], renewable energy resources integration and support schemes [15, 18–21], uncertainty and stochasticity in generation production and demand [10, 19, 22–25], demand side management (DSM) [26, 27], and smart-grids [28], among others. Reviews of the GEP problem can be found in [6, 29, 30], and a comprehensive recent review in [31].

In particular, as noted in the previous section, the need to combat climate through the decarbonization of the sector, as well as the advancements in the information and communication technology (ICT) has paved the way to fundamental transformations in both the electricity supply and demand of electricity). On the supply side:

- There is an increased shift from large synchronous generators to light-weight decentralized ones.
- There is an increased penetration of intermittent renewable energy sources (IRES), for which the investments are getting cheaper and the remuneration programs are becoming more attractive.
- There is an increased threat of power disruption due to extreme weather events.

On the demand side:

- There is a growing number of distributed variable generation resources, in the form of electric vehicles, electric solar production roof-tops, micro-grids, energy storage systems, among others.
- There is a usage shift of the demand from being passive (pure consumers) to being active (both consumers and small-scale producers, i.e. "prosumers").

This transformation is driven by technological advancement (e.g. the developments in the communication and control systems, affordable investments in renewable technologies), as well as by global energy policies with the aim of moving towards decentralized power generation and bi-directional power flow.

These developments are posing a number of pressing challenges that need to be adequately and methodologically addressed within the power system planning framework.

3 Electric Power Systems Planning Challenges

Traditional GEP models, based on step-wise load duration curves or other non-chronological approximations, have for long been appropriate for power systems planning, especially in systems dominated by dispatchable hydro-thermal units and with the primary concern of generation adequacy (e.g. [40–42]). These models have the main advantage of being computationally cheap, and therefore large sized systems and long-term planning horizons up to several decades can be easily optimized. However, when it comes to planning for system flexibility under IRES penetration, recent studies have started to show the importance of integrating the UC short-term constraints within the long-term planning model [9, 43–50].

Study [43] considers a combined GEP-UC model for planning over a single year, reduced to 4 weeks with chronological hourly representation, each week representing a season. In [9] a detailed formulation of the combined GEP-UC problem is provided and employed for the analysis of the Greek power system, under several scenarios of carbon emission pricing, emission caps, and IRES penetration targets. A multi-annual planning horizon is considered, where the year is approximated to 12 days, each one representing a month. The results reveal the correlation between significant IRES penetration with large amounts of natural gas production, which offers more flexibility to the power system. Similarly, in [44] a combined model for multi-annual planning is proposed and a clustering representation of the units in integer variables is presented. Several planning horizons are considered, where annual demand is reduced to a number of representative weeks selected in an ad-hoc manner. The comparison on the case study shows that when short-term constraints are considered, higher investments are driven to flexible peaking plants. In [45], a soft-linking between long-term and short-term models is implemented. The framework is to solve a long-term low resolution model to obtain a generation portfolio under a single IRES penetration scenario and to embed this portfolio in a short-term chronological model, which is solved multiple times with increasing level of technical constraints. It considers a case study for a single year and uses the number of units start-ups as a proxy for flexibility evaluation. A very similar approach is implemented in [46], but also varying the IRES penetration level. The impact of including several short-term constraints (most notably: startups/shutdowns, minimum stable load, ramping rates and operating reserves) is analyzed for a future planning year. Study [47] solves a planning model based on a basic screening curve method and proposes a perturbation algorithm with embedded short-term constraints to improve the plans obtained. A single future year is considered under different IRES penetration scenarios. A brief comparison of the results obtained pre- and post-implementation of the perturbation algorithm, in terms of the installed capacity, is discussed. It shows that considering the short-term constraints results in less installation of base load capacity compared to mid- and peak-load ones. Finally, studies [48, 49] compare the results of a fully integrated model to those of a traditional planning only model. The former work considers only a single future planning year, whereas the latter considers a multi-annual planning horizon of 10 years, where each year is approximated to 4 days in an ad-hoc manner. The comparison is based on the costs and emission levels resulting from both models, and shows that neglecting these constraints underestimates both attributes.

3.1 Operational Flexibility

Properly quantifying operational flexibility is critical for evaluating the overall system reliability. Whereas reliability relates to the fact that sufficient firm-capacity is available at each time period to satisfy the system load, as measured by typical metrics, such as loss of load expectation (LOLE) and expected energy not supplied (EENS), operational flexibility considers how a specific operational state of the system at a given period would contribute to (or hinder) its ability to deploy its resources for accommodating variations in subsequent periods: for this, no time period can be assessed in isolation of the others, nor without de- tailed knowledge of the exact system state and technical characteristics at the given period. Therefore, metrics to describe operational flexibility have been proposed in the literature, varying in the degree of complexity and in the data required for their estimation. The work in [51] proposes a probabilistic metric that takes into account key technical characteristics of the generation units and aggregates them for a system-level assessment. In [52], a number of interdependent metrics are defined for individual generation units to assess their available flexibility in real time. Study [53] proposes two flexibility indices to provide an offline estimation of the flexibility level of power systems. The first metric is obtained by analyzing adjustable space of generators, whereas the second assesses the flexibility level of a system by its capability for accommodating wind. Finally, [54] proposes a metric which additionally considers the impacts of the transmission network on the flexibility levels.

3.1.1 Research Gap

As shown, most of the studies reviewed argue for the benefit of including the short-term unit-commitment constraints within the long-term planning framework, especially in terms of answering to the flexibility requirements under increased IRES penetration, by analyzing the differences in capacity installation, production profile, emission and curtailment levels, system costs, or a combination of these. Those studies, however, do not resolve to using quantitative flexibility metrics to formally assess and compare the benefits of their proposed approaches. On the other hand, studies that have proposed quantitative flexibility metrics have often considered existing systems for the application and do not integrate those methods within the expansion planning problem itself. Furthermore, since the resulting expansion problem with unit-commitment constraints is computationally intensive, each study has resorted to a different combination of horizons reduction or ad-hoc approximation, neglecting to address the bias that this can impose on the results.

3.2 Resilience

Increasingly frequent and extreme weather events, such as heat waves, droughts, floods and storms, significantly affect the operational status of power systems. Evidence of power generation disruptions due to such events highlights the fragility of the existing systems and the need of considering resilience within the planning of future power systems [55].

Particularly, heat waves are among the most worrying weather extremes, due to the expected increase in their frequency and severity in the twenty-first century [56, 57]. For example, France was particularly impacted by the 2003 summer heat wave, which caused an excess of about 15,000 deaths from 4th to 18th August directly attributable to the heat [58]. By combining peaks of extreme temperature and severe soil and hydrological droughts, this event also affected significantly the energy production sector (mainly because of the cooling process of thermal power plants). These last years, numerous regions of the world experienced severe heat waves with comparable effects: Russia in 2010, Texas in 2011, Australia in 2012, India and Southern Pakistan in 2015. Therefore, it is of great importance to design the ability of the energy systems for coping with future heat wave events.

Among the research that studied the impacts of extreme weather events on power systems, [59] presents a multi-objective optimization of distributed power generation systems considering extreme wind and lightning events [60]. Proposes a probabilistic methodology to assess the resilience degradation of transmission networks subject to extreme wind events. In [61], an extreme weather stochastic model is applied to a realistic cascading failure simulator of power grids, accounting for the operating conditions that a repair crew may encounter during an extreme weather event. The impacts of water availability on the generation capacity expansion planning is investigated in [62] and the electricity sector growth is compared under different scenarios of water rights [63]. Proposes an integrated electricity and natural gas planning model taking into consideration the power grid resilience against storms, earthquakes and floods [64]. Studies the potential impacts of heat waves on power grid operation, by quantifying the capacity of thermal power plants as a function of ambient temperature.

3.2.1 Research Gap

Whereas most of those studies focus on evaluating the impact of extreme weather threats on the operation of power systems, there exist very few studies that incorporate resilience within the power system planning problem itself. Moreover, no study explicitly considers flexibility and resilience within a unified planning and assessment framework.

3.3 Uncertainties

Accounting for the inherent uncertainties in IRES supply and system load is another significant concern for ensuring reliable system performance. Two popular approaches have been often applied to address the uncertainties for the GEP and UC problems, separately. One is stochastic optimization (SO) [22, 24, 65–67], which models uncertain parameters by means of scenarios generated from probability distribution functions. This method may be suit- able if the probability functions are available, which is not always the case, and especially when considering long-term uncertainties such as in a GEP problem. Moreover, SO does not guarantee the feasibility of the solution for all possible uncertainty realizations, which is a significant limitation in addressing the operational flexibility issue. The other popular approach is robust optimization (RO) [68], which models uncertain parameters by means of distribution-free bounded intervals. RO is attractive in that it avoids the above-mentioned limitations of SO, but, it has been often criticized for resulting in over-conservative solutions and for being computationally intensive. State-of-the art RO methods deal with these problems by introducing an uncertainty budget parameter to control the conservatism of the solution and by resorting to efficient solution methods (such as Column and Constraint Generation (CCG) [69] or affine simplification of the recourse action [70]) to accelerate the solution.

3.3.1 Research Gap

Some research works have focused on RO-based approaches to handle uncertainties and address operational flexibility in power systems planning and operation. In [71], a two- stage adaptive RO model is proposed for long term generation and transmission expansion under generator output uncertainties but with no explicit consideration of the ramping requirements. Ramping was considered in [72] for power system planning but only through an approximated hourly load ramping uncertainty that is based on average net-load levels. Detailed ramping constraints were considered in robust unit commitment models such as in [73–76], but without considering the impact on power systems planning. Moreover, [75] has demonstrated how the two-stage robust UC model can lead to infeasibility in the dispatch problem when the generation ramping capability is limited. This showed the importance of considering non-anticipativity constraints in power systems operations within a multistage robust optimization. Yet, these results were not extended to investigate their impact on the power systems investment decisions.

4 Conclusions

Planning power systems for providing secure and reliable electricity to users is key in any energy strategy. This is being challenged by several recent developments, most notably, the increased penetration of variable intermittent renewable energy sources (IRES), which is raising concerns about the ability of future power systems to effectively respond to the high net-load variations, a system property which is referred to as operational flexibility. Moreover, climate change threats and, particularly, the increased frequency and severity of extreme weather events, are threatening to disrupt electric power supply and require the consideration of system resilience right from the planning stage. Also, the inherent uncertainties characterizing those systems must be inevitably considered.

To address the above-mentioned challenges, efforts must be devoted to developing efficient techno-economic modeling and robust optimization frameworks for multi-period generation expansion planning considering high shares of IRES and resilience against extreme weather events. The planning problem considers the technology choice, size and commissioning schedule of conventional and renewable generation units under technical, economic, environmental and operational constraints. Within this problem, key research objectives to be addressed are (i) the proper integration and assessment of the operational flexibility needs due to the increased variability from the high shares of IRES penetration, (ii) the appropriate modeling and incorporation of the resilience requirements against extreme weather events within the power system planning model and (iii) the representation and treatment of the inherent uncertainties in the system supply and demand within this planning context.

The framework will need to accommodate the fact that the economic planning parameters and the technical behavior of energy generation are affected by nonlinear conditions. For instance, production costs and ramping rates are nonlinear functions of the variations in partial-load levels, whereas start-up costs and times are nonlinear functions of the shut-down duration. These conditions become particularly relevant when short-term capabilities and operational flexibility are considered in the model. Then, the optimization model will need to give due count to the nonlinearities in the system. Moreover, the modeling and optimization framework should be applicable to multi-regional planning, accounting for the differences in weather conditions across the different regions. Also, potential benefits should be studied, of considering demand-side management policies, and/or different storage options as operational flexibility and resilience enabling resources.

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