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Impact of thermal plant cycling on the cost-optimal composition of a regional electricity generation system

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HIGHLIGHTS

- Thermal cycling impact the cost-optimal electricity system composition.
- 9–19% of investments are cycling dependent in systems studied with cap on CO_2.
- Cost-competitive, flexible thermal generation increases wind power investments.
- System characteristics which result in cycling dependent capacity are identified.

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ABSTRACT

A regional cost-minimizing investment model that accounts for cycling properties (i.e., start-up time, minimum load level, start-up cost and emissions, and part-load costs and emissions) is developed to investigate the impact of thermal plant cycling on the cost-optimal composition of a regional electricity generation system. The model is applied to an electricity system that is rich in wind resources with and without accounting for cycling in two scenarios: one with favorable conditions for flexible bio-based generation (Bio scenario); and one in which base load is favored (Base load scenario) owing to high prices for biomass. Both scenarios are subject to a tight cap on carbon dioxide emissions, limiting the investment options to technologies that have low or no carbon emissions.

We report that in the Bio scenario, the cost-optimal system is dominated by wind power and flexible bio-based generation, whereas base-load generation dominates the Base load scenario, in line with the assumptions made, and the level of wind power is reduced. In the Base load scenario, 19% of the capacity is cycling-dependent, i.e., for this share of installed capacity, the choice of technology is different if cycling properties are included, compared to a case in which they are omitted. In the Bio scenario, in which flexible bio-based generation is less costly, 9% of the capacity is cycling-dependent. We conclude that it is critical to include cycling properties in investment modeling, to assess investments in thermal generation technologies that compete at utilization times in the range of 2000–5000 h.

1. Introduction

The last decade has seen a drastic reduction in the costs for wind and solar power, making these generation technologies highly cost-competitive with other generation technologies with low or no carbon dioxide emissions. Combined with support schemes for renewable energy source (RES)-based electricity generation, this has resulted in the expansion of wind and solar power in several regions of the world, in a development that is foreseen to continue. This increased adoption of wind and solar power motivates the development of electricity system modeling methods that account for variability as well as variation management, such as thermal cycling. In dispatch models, cycling costs and cycling emissions from thermal generation are common features, as exemplified by the studies of Göransson et al. [1], Lew et al. [2], Meibom et al. [3], Bruce et al. [4], Troy et al. [5] and Mc Garrigle et al. [6]. Van Den Bergh et al. [7] present a further refined approach to account for thermal cycling in dispatch models. Göransson et al. [1] and Troy et al. [5] have shown how the inclusion of thermal cycling in dispatch modeling can modify the modeled dispatch order of the units in a wind-thermal electricity system. Van den Bergh et al. [8] show that cycling costs can be reduced with up to 40% if accounted for in the operation planning. Turconi et al. [9] show that, while cycling emissions do not negate the benefit of increased wind shares, emissions from cycling thermal

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generation are significant when evaluating life cycle emissions of the Irish electricity system.

However, the variability of wind and solar generation not only impacts upon the electricity system operations analyzed in dispatch models, but also affects the optimal generation mix; the need for electricity system investment models that take into account load and generation variability is well-recognized [10–12]. Investment models typically have a much lower time resolution than dispatch models, which means that the ability to capture the variable nature of wind and solar power has to be addressed specifically. Strategies that account for variability in investment modeling may be categorized into three different families: (1) methods that select time steps or time periods to represent the variations and use criteria that assure sufficient capacity; (2) methods that soft-link low-time-resolution investment models with high-time-resolution dispatch models; and (3) methods that add investments to models that have a high time resolution. The latter strategy is chosen for the model developed in this work.

A method that pertains to the first family of strategies is applied in the OSeMOSYS model described by Welsch et al. [11]. This method continues to rely on a low number of time steps but represents variability by gradually reducing the capacity credits of wind and solar power as investments in these technologies increase, while the required capacity is ensured by including reserve capacity. A second strategy from this family is the residual load duration curve (RLDC) approach of Ueckerdt et al. [13]. They derive an approximate load duration curve that consists of a peak that represents the peak load, a triangle that represents the intermediate load, and a box that represents the base load. They then evaluate, prior to optimization, how wind and solar power generation at different penetration levels affects the peak, the triangle, and the box. In the investment model, there are requirements for peak, intermediate, and base load capacities that depend on investments in renewable generation. A third strategy to account for variability in investment modeling is the "representative days" method proposed by Nahmmacher et al. [14], in which a number of days is modeled with chronological time and high time resolution within each day. The days are chosen to represent variations in load, as well as wind and solar resources. Methods that belong to the first family typically face challenges when accounting for variation management, since time does not follow a chronological order. The "representative days" method involves the chronological order of time within a day and can thus account for the diurnal variation management typically provided by batteries or demand-side management. However, the inclusion of reservoir hydro power and thermal cycling in all the methods belonging to this family is difficult, since their modeling requires consecutive time over long time periods.

The approach used in the SWITCH model [15] is a mixture of the method Families 1 and 2, and applies a method that contains a relatively high number of time steps (6 h per day for 2 days per month), accompanied by dispatch verification of capacity sufficiency. This approach could account for the reservoir hydro power, since the days follow a chronological order, although it would not be compatible with the cycling of thermal generation, which requires longer stretches of consecutive hours. Brouwer et al. [16] specifically addressed the role of thermal generation in future electricity systems by applying a method that pertains to Family 2 according to the categories suggested above. They combined a traditional investment model (MARKAL), which does not address variability, with a dispatch model that accounts for thermal cycling (Repowers). Deane et al. [17] have presented a similar approach using TIMES and PLEXOS to highlight the need for complements to traditional investment modeling, and Goransson et al. [18] have used the ELIN investment model together with the EPOD dispatch model to investigate the impact of demand-side management on transmission system congestion. Methods that belong to the family 2 models can take advantage of methods that account for variation management, including thermal cycling, as developed for dispatch models. The key challenge for methods in this family is the feedback of information from the dispatch step to the investment step. The lack of strategies to achieve convergence between investment and dispatch models implies in practice that the consequences of variations, in terms of (for example) thermal cycling, can be analyzed in detail but will not directly affect the investment decision. Vithayasrichareon et al. [19] evaluate a large set of system compositions, each optimal depending on which properties that are accounted for, with a dispatch modeling tool and calculate how cycling impacts on costs and emissions based on the modeling results. Their proposed approach, thus similar to other Family 2 approaches, combine a separate investment model and dispatch model, but avoid the need for iterations through the evaluation of a large number of system compositions. However, since accounting for cycling in the dispatch reduces the number of cycles [8], cycling costs and emissions from post-analysis risk to be overestimated. Also, the approach does not guarantee that a cost-optimal system composition is identified.

De Jonghe et al. [20] have applied a method (can be categorized into Family 3) to assess the cost-optimal generation mix. They have shown that wind power mainly increases the share of mid-load generation at the expense of base-load generation. The model used in their work has an hourly time resolution and is run for 1 year. Five technology options are considered in a single region (i.e., base, mid, peak, high peak, and wind power). Thermal cycling is accounted for by means of ramp rates. The main challenge facing this approach is the size of the model and the onerous calculation times, which impose limitations on the numbers of regions, years, and technologies that can be taken into account. Therefore, this approach is mainly suited to theoretical work on isolated systems and for single years, to reveal the characteristics of systems dynamics rather than for the modeling of existing systems.

The modeling developed and applied in this work can also be assigned to the third family. However, in contrast to [20], the present model focuses on the impact of thermal cycling on the cost-optimal generation mix, with detailed modeling of 11 thermal generation technologies, and including properties such as minimum load level and start-up time, as well as costs and emissions from starting and operating thermal generation in part load. The results obtained from this work complement and facilitate the interpretation of results from investment models that pertain to Families 1 and 2, where the cycling of thermal generation has been disregarded (Family 1) or only accounted for subsequent to investment optimization by means of some dispatch analysis (Family 2). Thus, the present work aims to provide guidance regarding the further development of methods to account for variability and variation management in investment modeling of electricity systems.

There are practical challenges linked to the inclusion of the cycling properties of thermal generation in investment models. The most straightforward way to model the cycling properties of thermal generation, as commonly applied in dispatch models, is to introduce one binary variable per unit and time step, which indicates whether a unit is online and ready for operation or not. Weber [21] has proposed a method to account for cycling properties that allows for the aggregation of units and that does not require binary variables. This approach was evaluated and compared to the binary approach in [22] and was found to provide good estimates of the total cycling costs for the system, as well as estimates of the full-load hours (FLH) on the technology level. The method proposed by Weber allows for the inclusion of cycling properties in models that analyze systems with a wide geographic scope, such as the EPOD dispatch model [22]. However, also for such an approach, accounting for cycling is costly in terms of