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Does cost optimization approximate the real-world energy transition?

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ABSTRACT

Bottom-up energy system models rely on cost optimization to produce energy scenarios that inform policy analyses, debates and decisions. This paper reviews the rationale for the use of cost optimization and questions whether cost-optimal scenarios are adequate proxies of the real-world energy transition. Evidence from ex-post modeling shows that cost optimization does not approximate the real-world UK electricity system transition in 1990–2014. The deviation in cumulative total system costs from the cost-optimal scenario in 1990–2014 is equal to 9–23% under various technology, cost, demand, and discount rate assumptions. In fact, cost-optimal scenarios are shown to gloss over a large share of uncertainty that arises due to deviations from cost optimality. Exploration of large numbers of near-optimal scenarios under parametric uncertainty can give indication of the bounds or envelope of predictability of the real-world transition. Concrete suggestions are then made how to improve bottom-up energy system models to better deal with the vast uncertainty around the future energy transition. The paper closes with a reflective discussion on the tension between predictive and exploratory use of energy system models.

1. Introduction

Jeremy Bentham (1748–1832), thought leader of classical utilitarianism, first used the words 'maximize' and 'minimize' to describe societal goals of maximizing utility and minimizing suffering [1]. These concepts were operationalized in the early 20th century, when mathematical optimization was invented. Since then, optimization was used extensively in mathematics, engineering, economics, and computer science. Since 1970s [2–5] and 1980s [6,7] bottom-up energy system models that rely on cost optimization for modeling global, national and local energy systems underpin many policy analyses, debates, and decisions. Such models have a detailed representation of energy service demands, energy resources, technologies and infrastructures, and they minimize total discounted system costs under technology, environmental and policy constraints. Often perfect foresight of future costs, technology availability, and service demands is assumed. The solutions of such models are energy scenarios for decades ahead. For example, National Energy Modeling System in the US [8] or MARKAL in the UK [9] are used to produce energy scenarios to assess national-level policy proposals or inform infrastructure planning decisions. Open-source OSeMOSYS [10] reaches experts in developing countries. Half of 30 integrated assessment models of climate change that inform the latest Fifth Assessment of the Intergovernmental Panel on Climate Change [11] are based on cost optimization; four fifths of these cost-optimization models rely on perfect foresight. The other half of these models implicitly use cost optimization rationale by prioritizing least cost technologies in their simulations. Other examples of widely used cost optimization models are TIMES/TIAM [12], MESSAGE [7], LEAP [13], TEMOA [14,15], Calliope [16], and many others.

Many of these bottom-up, perfect-foresight cost-optimizing models have evolved into large-scale, complex models that rely on thousands of parametric and structural assumptions. Although widely used, they have been criticized too. These models have been argued or shown to have systemic biases [17–19], to be based on value-laden [20,21], fragile [18] or narrow assumptions [22,23], to lead to irreproducible scenarios [24], and to have insufficiently broad system boundaries [25]. Retrospectively, the models did not capture structural changes in real-world transitions [23,26,27]. Detailed scenarios developed with such bottom-up models have been argued to be inadequate for anticipating long-term phenomena in face of deep uncertainties in technology, economy, and society [28–30]. When described in detailed narratives, such scenarios also tend to induce overconfidence because detailed

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scenarios seem more probable that the ones that have not been shown in detail [31]. As a result, there has been an increasing interest in model evaluation to assess the performance of models, cf. [32]. One of the unresolved critiques is the use of cost optimization [25]. This papers aims to assess the adequacy of cost optimization for modeling energy transitions.

Ever since the first bottom-up energy system models were developed, there has been a tension between exploratory and predictive use of energy scenarios. Nowadays modelers frame energy scenarios resulting from the models as possibilities what might happen and not predictions—that is, as scenarios “for insights, not numbers” [p. 449, 33]. But whether used for predictions or insights, scenarios generated with models are implicitly assumed to be able to give some indication of what is possible in the future and, in this way, are implicitly used as proxies of the future. From the multidimensional space of possible futures that is defined by technical, economic, environmental and other constraints, bottom-up models use cost-optimization to narrow down this space to one scenario to analyze further. But even intuitively one senses that real-world energy system transition may not be cost optimal. To date the bottom-up modeling community has been struggling to make the bridge between the need for scenarios that are reasonable proxies of the real-world transition and the models that cannot provide such proxies.

With the aim to resolve the aforementioned tensions and lack of ex-post evidence in bottom-up energy system models, this paper gathers historic evidence and conducts an ex-post modeling exercise in order to understand whether cost optimization approximates the real-world energy transition. The UK electricity system from 1990 to 2014 is modeled, using bottom-up electricity system model D-EXPANSE. With hindsight, the actual (real-world) transition is known and can be compared to the modeled cost-optimal scenario. As historic data on the model parameters, such as technology and fuel costs, are collected, the parametric uncertainty can be nearly eliminated in order to enable exploration of the cost optimization rationale. Due to its ex-post modeling approach, this study is the first of its kind.

This paper is structured as follows: Section 2 provides an overview why cost optimization is used in bottom-up energy system models and why it may be limited; Section 3 introduces the bottom-up energy system model D-EXPANSE; Section 4 describes the case and data of the UK electricity system transition in 1990–2014; Section 5 presents the ex-post modeling results; Section 6 discusses the results and proposes future research needs; Section 7 lists the implications for modeling the future energy transition with bottom-up energy system models; and Section 8 concludes.

2. Rationale for cost optimization and its limitations

Costs are among the key drivers of the energy system transition. On this basis, there are two interlinked arguments why cost optimization is used in bottom-up energy system models: the social planner's approach and the partial equilibrium argument. The social planner's approach originates in planning and public policy and assumes that there is a single decision maker, who aims at achieving the best outcome for the society as a whole. Such an outcome is reached by maximizing the sum of the energy supplier's and consumer's surpluses in the case of elastic demands. This surplus maximization is transformed into an equivalent of minimization of the total system costs that represent the negative of the surplus [12]. With fixed demands, only the total costs for suppliers are minimized. In reality, however, such a single social planner does not exist and, especially after market liberalization, multiple interacting energy suppliers and consumers with heterogeneous decision powers and stakes shape the energy transition [30].

The partial equilibrium argument assumes that energy supply-demand equilibrium is reached, when the total surplus, as in the social planner's approach, is maximized [12]. However, the general equilibrium assumption is not shared by institutional and evolutionary economists [34], while the partial equilibrium assumption does not account for the interaction between the analyzed sector and the wider economy.

In addition to these critiques of both the social planner's and partial equilibrium arguments, the heterogeneous actors in the real world do not always act rationally as assumed in models [35,36] and, if they do, there are other factors than only costs that they may consider [37]. Decision may be made using the principle of satisficing rather than optimizing, especially in face of multiple stakes. Energy transition is actively shaped by policy makers and other decision makers, who in the process require several alternatives to consider and choose from [15,38,39]. Neither posing one cost-optimal alternative for discussion nor expecting that it will be prescriptively followed is realistic. After all, the energy system is highly complex and it cannot be steered to a single least cost state anyway [40].

In light of such critiques, the bottom-up energy system modeling community has attempted to improve the models to deviate from cost optimal scenarios under perfect foresight to the ones that are believed to be more realistic. Such attempts include the myopic instead of perfect foresight versions [41], multi-objective optimization [42], analysis of parametric uncertainty [43,44], inclusion of external costs in addition to direct costs [45], models of multifaceted nature of behavior and decisions [30,46], second-best policy scenarios [47], near-optimal scenarios [39,48–50], or modeling constraints that enforce the deviation from cost optimality [51]. In addition, simulation rather than cost optimization models have been developed. Simulation models rely on historic evidence or theory-informed description of model variables to simulate the future scenarios, e.g. [52].

Even if ex-post validation and broader evaluation of models has been repeatedly called for [27,53], the handful of existing studies compared past scenarios and real-world transition on a generic level [17,23,26,27,31,54,55]. With the exception of McConnell and colleagues [56], no ex-post modeling studies exist that enable unpicking the reasons behind the mismatch of the modeled energy scenarios and the real-world transition. For example, such reasons could be cost optimization, parametric assumptions, structural assumptions, model boundaries, or others.

Recently, three-decades-old techniques [37,57] for exploring near-optimal solutions of optimization tasks have been applied to bottom-up energy models [39,48–50]. All these studies have showed that a small deviation in total system costs leads to a very diverse set of near-optimal energy scenarios. Keepin and Wynne [18] have already pointed out to this limitation of bottom-up energy system models, when small differences in input parameters, such as technology costs, cause large differences in solutions. Such limitation may not be resolved by multi-objective optimization. For example, Hara [50] has conducted vehicle mix optimization using two objectives of carbon emissions and costs. The resulting Pareto optimal solutions are less diverse than the near-Pareto optimal solutions, i.e. solutions that have up to 0.5% higher emissions (or costs) as compared to their respective Pareto optimal solution. In sum, the use of optimization tends to gloss over the diversity in possible near-optimal energy scenarios.

Even if the real-world energy system may not evolve in a cost-optimal way, costs are still among the key drivers. It is thus meaningful to assume that the energy system will not evolve in the most expensive and irrational way. Instead, the real-world transition will likely be somewhere close to the cost-optimal scenario, but not necessarily exactly the optimal one. Several modeling