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Modeling strategic objectives and behavior in the transition of the energy Sector to inform policymaking

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ABSTRACT

Transitioning the energy sector to zero or net-zero emission of greenhouse gasses (GHG) and substantially reducing other pollutants is a massive, costly, and long-term effort. The typical starting point and centerpiece of energy decarbonization is the electric power sector. The sector is a large direct GHG emitter. It already has many technological, non-carbon emitting alternatives that are rapidly declining in capital and operating costs and improving in performance, making electricity the least expensive and accessible energy carrier to decarbonize. This paper explores what the modeling community should do to inform this transition. The underpinning premise of this paper is that policymakers genuinely want to be informed from the modeling community about their range of options, their ability to achieve various objectives, and possible unintended outcomes. Since the goal of the modeling community is to help inform policymaking, it is important that they hear the needs of policymakers, be it economic, technological, or social goals.

1. The Electric Power Sector is Key to the Successful Transition of the Energy Sector

Transitioning the energy sector to zero or net-zero emission of greenhouse gasses (GHG) and substantially reducing other pollutants is a massive, costly, and long-term effort. It requires fundamentally restructuring, reorganizing, and rethinking the production, consumption, and economic regulation of energy in electricity, transportation, heating, manufacturing, and other sectors. Such an overhaul requires deep changes to society, and therefore policymakers must consider and evaluate the social, political, and economic aspects of this transition. From its inception, the design and implementation of this transition should anticipate and accommodate society's multiple objectives regarding equity and efficiency, sustainability, the inherent uncertainties in technological, economic, and social outcomes, the interactions between imperfect markets and imperfect regulation, and the strategic behavior of major actors. These actors include producers, consumers, market administrators, regulatory bodies, and political entities.

The typical starting point and centerpiece of energy decarbonization is the electric power sector for multiple reasons. The sector is a large direct GHG emitter. It already has many technological, non-carbon emitting alternatives that are rapidly declining in capital and operating costs and improving in performance, making electricity the least expensive and accessible energy carrier to decarbonize. It produces an energy carrier that can be substituted for fuels in other energy subsectors such as transportation, manufacturing, and heating, which currently are each dependent on a single fuel. The electric power sector's extensive network of transmission and distribution lines allow it to integrate and deliver electricity produced from different primary fuels, and hence it is the foundation for society-wide deep decarbonization. It has a long history of diverse economic and environmental regulation at the federal and state levels that can and is being employed to achieve this transition. For these reasons, the role of electricity in the energy transition will increase with the electrification of much of the transportation sector and additional electrification of the building and manufacturing sectors.

Importantly, there is already an extensive, sophisticated, and robust set of modeling tools that were developed to evaluate the prior transition to a liberalized power sector that can be deployed to analyze and propose energy decarbonization plans. Many off-the-shelf software models of the electric power sector, such as Plexos, Promod, RADAR, IPM, Polaris, among others, are routinely used by government, industry, and researchers. Improving these tools, expanding their functionality, and creating new ones that address current and oftentimes changing policy

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priorities are instrumental in advancing the energy transition. The ability to analyze multiple objectives with various uncertainty and fluctuating factors, that is to solve stochastic optimization problems, and numerous strategic players can provide important insights and guidance to policymakers aiming to achieve decarbonization in a cost-effective, politically sustainable, and socially inclusive manner (Hobbs et al., 2016).

This paper explores what the modeling community should do, not the reverse, i.e., what policymakers should do. The underpinning premise of this paper is that policymakers genuinely want to be informed from the modeling community about their range of options, their ability to achieve various objectives, and possible unintended outcomes. Since the goal of the modeling community is to help inform policymaking, it is important that they hear the needs of policymakers, be it economic, technological, or social goals. Non-economic objectives can be incorporated into modeling efforts, if desired, which will both respond to policymakers' needs and inform them of the associated tradeoffs between objectives.

2. Modeling of the electricity sector was instrumental in its liberalization

Throughout the world, many policymakers implemented electricity markets and regulatory reforms within the broader context of liberalization of other industrial sectors including oil and natural gas to achieve multiple political and policy objectives. The inception of the sector's economic liberalization in the early 1980s leveraged academic work from the 1970s and afterwards that connected these engineering models to "economically efficient" markets and outcomes: the least-cost solution to generate electricity also provided, under the correct economic and mathematical conditions, economically efficient prices. Liberalization efforts leveraged the fact that the operation and planning of the electric power sector are hand in glove with optimization models of economic dispatch, unit commitment and expansion planning (Schweppe et al., 2013).

In electricity markets, the stated goal of liberalization was singular: economic efficiency. Under the assumption of perfect competition, market completeness and convexity, and in the absence of market failures, the energy prices that came out of cost-minimization models were socially optimal, signaling efficient supply and demand operational and investment decisions, with the ability to manage congestion risk using congestion contracts such as financial transmission rights (FTRs) combined with scarcity pricing that reflects the value of lost load and the loss of load probability, or through capacity markets, which, at least in theory, could do the same. In electricity modeling, however, both missing market positions/states and use of direct current power flows instead of alternating current can hamper the ability to appropriately approximate reality. Furthermore, instance on convexity, which improves model tractability, has important implications for market design and modeling, e.g., convex hull pricing of generation start-up costs (Schiro et al., 2015). These types of models were solved routinely and quickly using off-the-shelf software (as well as vendor specific platforms) based upon advances in both algorithms and computational speed.

As the liberalization of the power sector unfolded, however, it became clear that electricity markets violated the underlying economic and mathematical assumptions. For example, the exercise of market power by owners of generation unit fleets has become a major concern as many characteristics of electricity markets make them very susceptible to market power such as the need to instantaneously balance supply with an almost inelastic demand due to policies that hinder price responsiveness; transmission constraints, as well as various contingencies, that limit competition between producers; reliability rules that must be met almost no matter the cost, and economies of scale that favor large generation fleets, with ability to affect market outcomes. When assumptions of perfect competition in energy and capacity markets do not hold, cost minimization models, especially for capacity expansion, are no longer guaranteed to produce realistic market outcomes. Similarly, assumptions about full information and lack of externalities were routinely violated.

The modeling community responded to these issues by formulating problems, developing models, and improving algorithms that could accommodate strategic actors with different and composite objective functions that include many components that are difficult to formalize in cost-based decision making (Kim et al., 2020; Maloney et al., 2020). Major objectives are themselves the composition of subobjectives. For example, policymakers frequently articulate the goals of resilient and secure electricity, which can overlap with reliability goals. These strategic actors are also advancing their interests within the complex set of power flow equations and generation, transmission, and reliability constraints. The linkage between optimization and strategic behavior is longstanding – linear programming has been used to model strategic games for decades – but the challenge is accounting for the non-convex structure, which may give rise to multiple equilibria, in a tractable manner, while sufficiently capturing the realism of the problem at hand including numerous heterogeneous actors. These types of complementary problems are further classified as mathematical programs with equilibrium constraints (MPEC) and equilibrium problems with equilibrium constraints (EPEC) (Gabriel et al., 2012).

3. More modeling advances are needed for the energy transition to succeed consistent with social objectives

This connection of engineering models with economic markets was vital to the electric sector's liberalization, but it only serves as a starting point for the broader energy transition. A successful transition, however, involves much more than a mere reduction or the elimination of GHG emissions at the lowest cost possible. For it to be a success, the transition must result in inclusive public participation, lead to affordable access to clean energy for low-income communities, and a fair distribution of the benefits of the transition to historically marginalized communities, while minimizing any additional costs to already environmental and energy burdened communities. The energy transition, therefore, is a multiple objective problem that requires further work in modeling.

Furthermore, for several reasons, policymakers have not fully embraced the wholesale market objectives and models presented above. Some dispute whether wholesale markets achieve their stated aims, and others dispute the primacy of these aims. As just discussed, policymakers pursue other objectives besides economic efficiency or even cost minimization such as the rapid decarbonization of the power sector, particularly with non-pricing and out-of-market mechanisms to garner political support by targeting industries to demonstrate economic development.

For example, there is a strong, but at the end of the day insufficiently compelling, case that the design of wholesale markets has been solved both in theory and in practice given political forces. Locational marginal pricing based upon real-time and day-ahead unit commitment produces economically efficient prices so long as regulators address market power and asymmetric information that arise between the market and market participants and implement policies such as an optimal pollution tax or emission cap-and-trade regime to internalize the external costs of electricity generation related to emissions. However, policymakers are reluctant to have high or volatile energy prices, or pollution taxes, leading them to opting for less efficient, second-best policies. Furthermore, the increasing penetration of renewable resources with zero or near zero marginal costs is challenging this pricing mechanism. Can markets dominated by renewable energy be designed that produce economically efficient outcomes and are accepted politically, that is to clear at sufficiently high prices for sufficiently long time periods to pay for new clean energy investments while maintaining grid reliability and accessibility of electricity supply?

Much of the U.S. has adopted the above-described wholesale market design but with a major modification, capacity markets, to ensure resource adequacy instead of having sufficient shortage pricing to clear the real-time energy market (Jaffe and Felder, 1996). These capacity markets have undergone numerous reforms since their inception and may need to continue to evolve with the expansion of renewable generation. In addition, approximately half of the U.S. states have renewable portfolio standards (RPS) that use a market-like mechanism to subsidize different types of renewables instead of or even in addition to carbon-pricing policies. States tailor their RPS to the type of renewable resources available in the state as well as to broader economic development and political needs. In contrast, pricing of carbon has proceeded regionally, such as the Regional Greenhouse Gas Initiative (RGGI). Finally, transmission investment is not conducive to a market mechanism because of its underlying lumpiness and AC flow characteristics, but the evaluation of various transmission investments does depend significantly on market outcomes including their level of competitiveness. As a result, developing a planning process within a regulatory framework that efficiently invests in transmission given electricity markets has become a major modeling challenge. These and other departures from the idealized model continue to motivate modeling advances.

The policy push for rapid decarbonization, the advances in performance and cost of renewable resources and energy storage technologies, the underlying stochastic nature of grid operations and planning due to random outages of generation and transmission facilities, uncertainty in demand require, and intermittent renewables require advances in modeling uncertainty. In addition to improving model formulations and algorithms, more complete and accurate data sets are needed to assess the probabilities of different events. The ARPA-e GRID Data effort is a solid starting point but should be expanded to encompass broader industry and, most importantly, socio-economic data. Relatively small changes in probabilities can have dramatic impacts on modeling outcomes, particularly for low-probability, high-consequence events, such as blackouts and large-scale outages due, for example, to extreme weather events (Felder, 2001). It is therefore important to integrate the analysis of multiple objectives, such as using Pareto frontier analysis, with uncertainty analysis, and work in this area continues to advance, for example with the recently proposed Pareto Uncertainty Index (PUI) (Selçuklu et al., 2020).

Other new issues and therefore modeling challenges arose. Increasing renewable penetration created new challenges to instantaneous balancing, and this is one example of the need for improved stochastic methods and richer data sets. Energy storage brought additional challenges to understanding the effects of market power, as it enables off-peak producers to compete with on-peak producers, which increases competition, but only if its ownership is sufficiently diffused to prevent its operation to be used strategically, e.g., by coordinating their operation with other generation or transmission assets.

Policymakers, market participants, and stakeholders do not select their objectives or proposed means in a vacuum. They behave strategically, and they advance their interests with guile (Felder, 2002, 2012). As a result, claimed objectives may not be actual ones but may be selected and promoted to shift the political dynamics in anticipation of or in response to other competing interests. For example, the stated policy motivation for power sector liberalization in the U.S. was economic efficiency, but politically the objective was lower prices.

In the U.S., the split jurisdiction between States and the federal government enables strategic behavior that models need to incorporate (Kim et al., 2020). This jurisdictional split opens the possibility that federal regulators, responding to federal policy, have different objectives than individual states. The recent debate regarding the Federal Energy Regulatory Commission's (FERC) Minimum Offer Pricing Rule (MOPR) in which the federal government emphasizes efficient market objectives (although ignoring the negative GHG externalities), whereas states are interested in accelerating the adoption of renewable resources by using a second-best solution, i.e., renewable portfolio standards, with its attenuate implications for efficiency illustrates the point of different objectives and the strategic behavior of policymakers.

4. Advancing the modeling of the future electric power sector to support policymaking in the energy transition

Incorporating multiple objectives and manifold actors behaving strategically in a framework consisting of large uncertainty, while accounting for the physics of power systems, is at the edge of the capabilities of current optimization models. Furthermore, there are additional factors that are also stretching this type of modeling. New power system designs are being proposed that involve the distribution system and distributed resources (generation, storage, and loads) (Revesz and Unel, 2020), the interconnection of the power sector with the natural gas system, transportation electrification, and the increasing emphasis on reliability and resiliency. Figuring out how to evaluate and compare all these potential developments and the appropriate policies could benefit from systematic optimization modeling. Fig. 1 illustrates the connection between the physical design of the grid and the incentives that motivate business and regulatory actors.

Enhanced grid data and its availability to policymakers, models and algorithms can inform policy in three ways. First, the results of specific models may be able to explicitly quantify outcomes that provide policymakers with the information they need to base their decision upon. Improving modeling efforts should give more confidence to the produced results and associated decisions. Second, models can provide conceptual and qualitative insights that also improve policymaking. In the case where uncertainty is substantial or the problem at hand requires major abstractions to make models tractable, this may be the best outcomes that the current modeling technology can provide. Finally, optimization modeling may help with evaluating future power sector designs and transition scenarios.

Structuring the design problem of the future grid as an optimization problem, even if not explicitly solved, provides value. It forces identifying the objectives, linking them to decisions that policymakers must make, articulating the linkages between decisions and outcomes, and establishing the limits on individual and collective decisions. Currently, much of the discussion of the future of the grid is on individual proposals or pathways. As individual pathways are fleshed out, cost-benefit comparisons among them will be necessary. If these comparisons are not done on a common footing, it will be difficult for policymakers to tease out which pathways they should be preferred due to the objectives they accomplish or due to better designs. Successful completion of this work could lead to having individual pathways described with sufficient degree of precision to being able to apply stochastic planning with pathways serving as the scenarios.

The design of the future grid exemplifies the application of advanced power sector modeling to inform public policy along technical, economic, political, and social dimensions. This discussion is organized around identifying the objectives, strategic variables, and major uncertainties. The future grid design objectives are manifold. A review of the objectives of the future power sector from major reports (see Table 1) results in the following list: efficiency, affordability, reliability, innovation, health, sustainability, economic development, climate change, sustainability, and equity.

The first step involves identifying the objectives that the electric grid is expected to fulfill. These include sectoral objectives, such as maintaining reliability, increasing efficiency, and setting electricity tariffs so that they best reflect the true costs of generation, transmission, and distribution of electricity to the consumers. These impacts can be quite disparate and lead to conflicting decisions. Fig. 2 shows the level of reliability within Manhattan, and within several blocks the levels vary substantially. It is important to distinguish between final and intermediate objectives. For instance, reducing generation or transmission outages is an intermediate objective to the final objective of improving reliability.

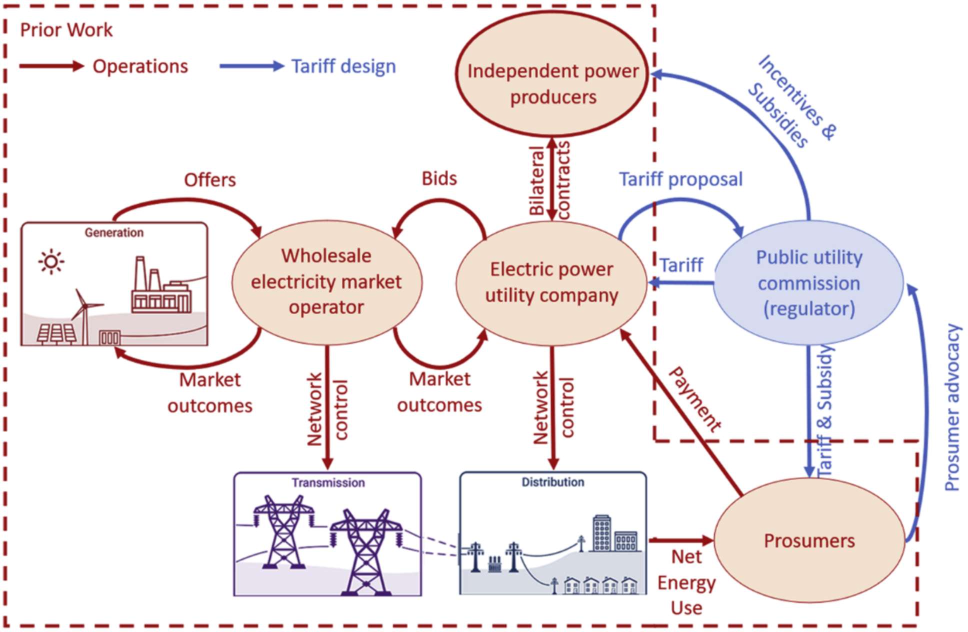

Fig. 1. Designing the Future of the Grid: Assets and Actors.

Table 1
Different and Evolving Objectives for the Power Sector.

S. No.	Objectives	MIT, 2011	NREL Report, 2013 Cochran et al. (2013)	NY-REV, 2015	QER, 2017	CRS Report, 2018	DOE, 2019	APP Report, 2019
1	Promoting efficient power systems operation	✓	✓					
2	Creating clear and effective incentives for investment	✓	✓				✓	
3	Improving reliability and cost-effectiveness of electricity service	✓	✓		✓			✓
4	Encouraging clean energy/ power-system innovation.		✓	✓				
5	Reducing the health-impacts of electricity service		✓					
6	Providing consumers more affordable electricity	✓		✓		✓	✓	
7	Encouraging competition			✓				
8	Improved sustainability/Meeting environmental/ climate-change mitigation goals/Building clean electricity future	✓	✓	✓	✓	✓	✓	✓
9	Building a more resilient energy system			✓	✓		✓	
10	Creating new jobs and business opportunities			✓				
11	Improving existing infrastructure			✓				
12	Supporting cleaner transportation			✓				
14	Enhanced security				✓	✓	✓	
15	Maximizing economic value and consumer equity				✓			

In addition, the power sector is expected to meet broader societal objectives, namely, reducing adverse environmental and health impacts, managing carbon emissions, creating jobs, and supporting economic development, especially for communities that are historically overburdened and underserved. For clean energy transition to be a tool for, and not a barrier to, environmental, energy, and climate justice, efforts should also focus on modeling outcomes important to these societal objectives at a temporal and locational resolution meaningful for policymaking.

Once the decision-makers agree on a set of objectives for the power sector, the process of evaluating the proposals that best meet these objectives can begin. The challenge then is to assess what are the underlying objectives of different options, and to evaluate whether they are in line with the objectives that policymakers want the electric grid to achieve.

The strategic variables for this design problem are the technological strategy, institutional structure, and level of competition versus regulation. Beyond the science of the mathematics, the art is how to formalize these variables, and relationships among them, in a way that would be suitable for decision analysis with existing and improving modeling tools. The technological strategy encompasses choices regarding centralized versus distributed resources, the rate of introduction of smart grid technologies throughout the grid, how power can flow on the system, e.g., one-way or bi-directional, and the grid's interconnection with other infrastructure systems, in particular natural gas and transportation. Institutional structure relates to the types of organizations, their tasks, and incentive structure in regulating, planning, administering, and operating the grid. For instance, should there be Distribution System Operators as body in charge of distribution operations independent of commercial interests, and if so, what are their roles, responsibilities, and incentives and how do they fit in with regional transmission organizations (RTO), if at all? Finally, there is a continuum of choices along the regulation-competition axes regarding resource investment and operational decisions that must be made.

These three variables are interdependent and the selection of an option for one variable can simultaneously restrict and expand the choices of the others with the challenge being how to represent these interdependencies in models. For instance, if the technological strategy is widespread distributed resources, then a consistent institutional strategy would focus on distribution systems and not centralized

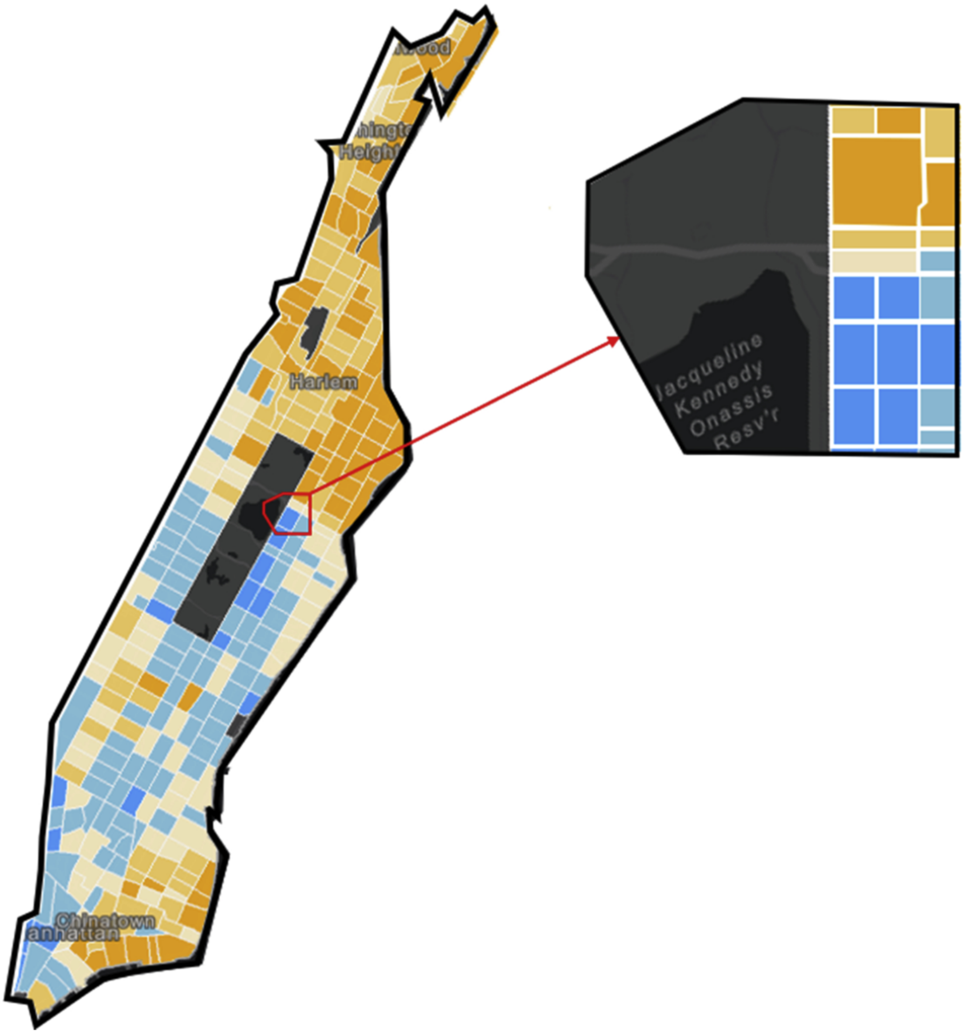

Fig. 2. Disparities in Reliability In Manhattan, New York City.

generation and transmission and perhaps lean more to using markets than regulation. In the design process, after specifying the objectives, the next task is identifying which technological, institutional, and regulatory strategies are internally consistent and then to evaluate solutions from this set regarding their ability to achieve the desirable objectives under uncertainty.

The subsequent step is to evaluate different proposals and identify the ones that best meet societal needs. For this, it is important that the proposals are complete for them to be comparable. For a proposal to qualify as being complete, it should identify the outcomes of the proposal such as emissions reductions, reliability and resiliency enhancements, and system efficiency. It should also identify different technological solutions and/or institutional frameworks that help in achieving the aforesaid outcomes. Finally, proposals should also identify the risks, uncertainties, and unintended consequences associated with different proposals. It is important that the modeling is granular enough to assess distributional consequences, both in terms of costs and benefits. Without locationally and temporally granular modeling outcomes, it is impossible to understand how the transition could affect locationally-diverse demographic groups, especially historically marginalized communities. Similarly, as different demographic groups have different energy needs and use profiles, risk tolerance, and vulnerabilities to outages, an understanding of how and when different communities could be affected is a key for a just transition.

A systemic analysis should attempt to assess the uncertainties and bring out how those uncertainties could impact the outcomes. Further, the analysis should also genuinely identify and reflect the unintended outcomes for a meaningful comparison of different proposals. For example, if large-scale off-shore wind becomes comparatively cheaper in the next decade, and the objective of the power sector is to reduce costs, then utilities with substantial off-shore resources may find it advantageous to invest in strengthening the transmission infrastructure, rather than investing in distributed resources. Thus, every option must have discussion around underlying risks and uncertainties, their impact on specific proposal's outcomes, and validity. Once different options of the proposals are comprehensively described with a full understanding of their strategic choices and interactions, the next step is evaluating how these individual options compare with each other followed by which are the options best fulfill the desired objectives.

The optimization framework breaks down when considering alternative futures for the power sector becomes a design problem with major open-ended objectives and variables that are hard if not impossible to quantify. These variables could be decision-critical, i.e., so fundamental that they redefine the decision space and underlying philosophical questions of values and objectives that do not lend themselves to being quantitatively modeled. Nonetheless, once particular designs are conceptualized, optimization models with the augmented capabilities discussed above and elaborated below, can help, perhaps tentatively and partially, with design evaluation by feeding back modeling results to make design adjustments and fashion new ones.

5. Research agenda linking substantive and process improvements in modeling with improved policy outcomes

The prior discussion recommends both process and outcomes that the modeling community should pursue. With the wide-open nature of next-generation power sector and broader energy sector designs given the policy push for rapid decarbonization, publicly available datasets and models are a priority. Strategic actors with competing and overlapping objective functions will not likely accept the results of models and their underlying data sets that are not transparent, and even if they can afford to construct their own modeling platform, which many cannot, they may use this as an excuse to dismiss the modeling results. Furthermore, the need to include more stakeholders and achieve more equitable outcomes is a further motivation for transparent modeling. Of course, reasonable confidentiality and data copyright concerns should be addressed.

Modeling efforts by governmental and other organizations should be viewed as ongoing activities, not one-and-done projects. RTOs and Independent System Operators (ISO) can be important players in the development and application of models to address the power sector transition. They have access to vast amount of power system data, have extensive expertise in the engineering and economics of the power system that they plan and operate, and have in place stakeholder processes that allow for the dissemination and discussion of modeling results. Currently, RTOs approach the modeling of the transition as one-time activity the Future Pathway project in New England is an example. A series of modeling analyses are being conducted, coordinated by the ISO-NE and NEPOOL, to investigate and inform future market designs under deep decarbonization.[1] However, segmented efforts that do not incorporate the treasure trove of advanced metering infrastructure (AMI) data, are bound to misrepresent how the demand is evolving as well as underrepresenting the flexibility that consumers with new technologies can afford, and air emission and pollution data such as detailed emission data from generation units less than twenty-five megawatts and air quality measurements.

Substantively, the modeling research agenda should include the following components. First, the integration of optimization models from first principles – engineering, economic, political and social – with the tremendous capability of computers supporting machine learning applications to process large amounts of data and construct accurate predictive statistical models. What combination of optimization and simulation and intuitive versus data-rich models work best for which modeling applications and policymakers is an open research question. How to extract insights regarding the fundamental dynamics from integrating these modeling approaches needs to be answered. It will be tempting for some to use opaque, big data models (and optimization models to be sure) to push policies hiding behind claims of large data sets and advanced machine learning techniques as opposed to informing the policy community.

Second, the modeling paradigms should start to switch from pure cost- and firm-centric modeling paradigms to include customer-centric objectives. At best, consumer preferences are currently represented with a generic penalty for load-shifting. However, with increased deployment of distributed energy resources, and electrification of transportation and heat, it is even more important to model how consumers make their choices – maximizing their utility, which is difficult to formalize mathematically, and not necessarily minimizing costs. While the two would be equivalent under certain assumptions, which are often invoke for mathematical convenience, new technologies and smart appliances have started to allow more flexibility and control to consumers in how they produce and consume energy. Yet, current models are still far from being able to capture consumer preferences over thermal and non-thermal loads, when and how much they are willing to shift, and how these interact with traditional economic factors that affect energy demand such as temperature, which will be critical as extreme weather events will occur more frequently.

Third, given the wide range of objectives that policymakers are pursuing, linking models of the power sector with air quality, climate, and macroeconomic models must also be done. To date, these efforts are slow, cumbersome, and expensive, all qualities that limit their immediate use in policymaking. In the case of air quality and macroeconomic modeling, to capture the complexity of the underlying processes requires standalone models that cannot easily be reduced to a manageable set of equations that can be integrated with a power system model. Current approaches are to either have separate models that are coupled with feedbacks between them or use a reduced form model that integrates both. Even though the underlying processes for such modeling are complex, improving modeling in these dimensions is crucial to understanding environmental and climate justice impacts of the transition. Therefore, it is important that they are a part of the core research agenda for the modeling community over the next decade.

Fourth, with the structural changes in the power sector, modeling should be employed not just to answer specific questions but to inform design decisions. A specific model formulation assumes a particular design, and the challenge is for the modeling community to step outside of the implicit framework that the model is embedded in to apply modeling techniques to inform and evaluate possible designs. For instance, models that calculate distribution locational marginal prices, or their variants, on distribution systems are working within a design framework of distributed resources. How such a design compares with other ones, let alone whether it is preferable also needs to be evaluated. Choices about model formulations should be linked with regulatory, governance and market design and not limited to improving the tradeoff between accurately reflecting the problem at hand and mathematical tractability. One quick illustration of this point is the selection of hard versus soft constraints in a model, where “hard” and “soft” are defined as tolerance of the decision maker to the frequency and magnitude of violations. The representation of technical, economic, or political requirements as a cost or hard or soft constraint is characterizing the problem in an important way that may not accurately reflect the underlying problem the policymaker is trying to address.

Fifth, economic, policy and social forces that result in constraints to be considered and selected in optimization models come from other optimization models, in many cases of those of other strategic actors. The modeling work on electricity market power illustrates this point explicitly. Other examples, however, are not explicit, such as the inclusion of renewable portfolio standards (RPS) as constraints in a wholesale electricity market model. These RPS constrains arise from a regulator’s decision-making (that was perhaps not explicitly written out by the regulator or thought of in these terms), but by formalizing the regulator’s problem even if analysts do not explicitly solve the combined RPS-market problem, they may obtain some valuable insights. When modeling the strategic behavior of multiple actors, multiple equilibria may result. Characterizing and interpreting such outcomes in a policy context are open questions that need to be addressed.

Sixth, transparency, accountability, and understandability of the modeling efforts is increasingly important. There have been significant strides on this point, with more modelers opting to develop their open-source platforms. However, these models are still hard to understand, each with their own hard-to-validate assumptions, non-standardized data sources. Even interpreting their results and limitations requires highly specialized knowledge of electricity markets and an understanding of power system modeling, making the models inaccessible to their target audience. With trying to increase public participation in policymaking becoming a social justice priority, developing transparent and accessible documentation for open-source models, and improving how these models communicate should also become a standard part of modeling development (Unel et al., 2020).

Finally, building models for research is not the same as building

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[1] See https://nepool.com/future-grid-initiative/,assessed July 19, 2021.

models for real-world applications such as in policy analysis, although there is substantial overlap. Researchers value novelty, mathematical intricacy and advances, conceptual improvements, and generalizability. Policymakers emphasize familiarity, customizability, and data-rich models that are readily applicable to the task at hand. They value speed over precision, especially when the variation in outcomes of their interest is not high enough to change the policy recommendation. Communicating across these divisions requires the fundamental appreciation from analysts regarding what questions policymakers have and why they look to models to inform answer these questions as opposed to some other means. Modeling for public policy also requires a careful balance between capturing context and details that are important to policymakers, even if not explicitly needed in the model, and tractability. One thought experiment for analysts is to try to infer the policymakers' mental models that they are using. In many cases, these mental models are implicit and embedded into the policymakers thought process that, if confronted with a different answer from an analyst's model, could be rejected out of hand as patently wrong. For example, if a policymaker's implicit mental model is that it more economical for a state to have a product produced in that state, then an economic analysis that confronts this assumption may not be seriously considered by policymakers. Trying to backout a policymaker's embedded mental model, granted a challenging and error-prone exercise, may help connect these two modeling domains of research and policy application.

6. Final thoughts

Of course, policymakers, once their decisions have been made, might be tempted to cherry pick models based upon results, rhetorically shift the analytical basis for those decisions, and dismiss or downplay counter evidence. Nonetheless, there is a window of opportunity for the modeling community to inform policymakers before firm decisions are made.

Improved modeling of power systems in the context of strategic actors with multiple objectives under uncertainty across competing systems of market and regulation will not resolve the underlying philosophical and political disagreements. Political outcomes and their underlying framework are based upon forces and dynamics that are broader and above the internal debates within the power sector regarding what its objectives should be and how to best organize and structure the system. Better data, algorithms, and open-source models, if properly employed by analysts in response to the political and policy needs of decision makers, will help sharpen thinking, focus attention on relevant issues, and help avoid major incongruities and inconsistency in policy that would, if left unattended, result in undesirable and sub-optimal outcomes.

Declaration of Competing Interest

The authors report no declarations of interest.

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