The Pace of Decarbonization: Can the Power System Transition Meet Climate Policy Goals?

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Abstract

To reach net zero greenhouse gas emissions by 2050, the United States will need to simultaneously expand and decarbonize its electricity supply. Aggressive clean energy policies supported by socially-aware modeling frameworks are necessary for the pace of the transition to meet this goal. Policymakers rely on computer modeling to inform decarbonization policies, even though most power sector models were not developed for this purpose. This paper investigates elements of modeling that are, and are not, constructive for climate policy design through a case study of Massachusetts. The analysis discusses typical uses for modeling results in the context of recent energy projects, in order to highlight strengths and weaknesses of power sector modeling as a tool to inform policy making.

The discussion acknowledges what all modelers know – that modeling is useful for identifying technically feasible options and for comparing them based on quantifiable indicators. Frameworks such as general equilibrium modeling notwithstanding, this paper asserts that power sector models are incapable of identifying socially optimal solutions and estimating achievable pace of decarbonization, because they necessarily omit underlying social dynamics that affect policy implementation and decarbonization goals.

Keywords: Modeling, climate policy, decarbonization

1. Introduction

To succeed in limiting global warming to 1.5°C, global anthropogenic CO_2 emissions must reach net zero by 2050, and non-CO_2 emissions must reach net zero by 2070 (IPCC, 2018). Accounting for its historical emissions and ongoing economic capability, the U.S. is in a position to act even more aggressively in reducing carbon emissions (CAT, 2020). The power sector is foundational to economy-wide decarbonization, given that significant emissions reductions can be achieved by pairing low-carbon electricity generation with increased energy efficiency and electrification of other sectors in the economy (DOS and EOP, 2021).

The power sector is currently the source of one quarter of U.S. greenhouse gas emissions (EPA, 2022), and electrification in the transportation, buildings, and industrial sectors will cause demand for electricity to grow. The power sector therefore faces the challenge of simultaneously expanding and decarbonizing the electricity supply. Wind and solar energy have low operating costs and abundant resource potential, and are commonly identified to contribute a large share of low-carbon generation. Their performance characteristics differ significantly from those of synchronous generators though, so wind and solar resources present a number of well-known technical challenges for grid operation. Two such challenges are balancing electricity supply and demand across all timescales, and providing reliability without relying on the rotational inertia of synchronous generators (Denholm et al, 2021).

Wind and solar are known as variable renewable energy (VRE) because their ability to produce electricity depends on resource availability. VRE resources are connected to the grid via inverters, and as inverter-based technologies gain prominence within the power supply, alternate techniques for the provision of ancillary services such as voltage and frequency regulation are necessary.

Another significant obstacle to widespread VRE installations is siting issues. Not only do wind and solar facilities require significant land area themselves, but they may also be located far from load centers and existing transmission infrastructure, and require the construction of new transmission lines to be connected to the power grid. It is often this second obstacle—siting—that prevents implementation of planned VRE installations.

1.1. Pace of power sector decarbonization

Without explicit climate-based intervention, the electricity supply will decarbonize too slowly to meet policy goals. The underlying challenge identified in this paper is the need to decarbonize *rapidly*, which will require both a change from the historical slow pace of power system evolution and also require realigning system expansion projects with society's "energy acceptance" (discussed in section 3 below).

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The benefits of increasing the use of VRE technologies is clear to many researchers, system operators, policy makers, and communities. The financial costs of VRE have declined precipitously in recent years, making renewables less expensive than new fossil fuel generation in many cases (Lazard, 2020). Even without accounting for the externalities of fossil fuel combustion, expanding the share of VRE in the fuel mix is economically viable.

However, the slow turnover of infrastructure, as well as numerous sources of friction in this transition—ranging from the influence of entrenched fossil fuel interests to the difficulty of siting large clean energy projects—means that the transition will occur slowly without focused efforts to decarbonize. Targeted climate policy in the energy sector is required to decrease the use of fossil fuels more quickly than is occurring with our existing policy and modeling mechanisms.

Decarbonizing the power sector is therefore both a technical and a policy challenge. Access to technologies such as low-cost VRE is important. Equally important are policy mechanisms that will drive the rapid deployment of these technologies, and ensure public acceptance of the proposed VRE projects.

This paper uses a case study of Massachusetts to illustrate which types of policy-relevant information power sector models are capable of providing (Metz, 2022) and to investigate the question "Why are projects with clear technical benefits not successfully brought to completion?"

2. Clean Energy Policies in Massachusetts

As a representative discussion on the consequences of unsuccessful societal energy acceptance, this section presents a number of failed energy projects in Massachusetts. The state recently enacted an economy-wide emissions limit of net zero by 2050 that will need to be backed by ambitious power sector policy. Massachusetts already has a number of policies in place to reduce power sector emissions, and these will need to be expanded for the state to reach net zero emissions. Three of the most significant are the renewable portfolio standard, RPS (Mass, 1997), the clean energy standard, CES (Mass, 1997), and Energy Diversity Act procurements (Mass, 2016), discussed below. There are also a variety of smaller programs to address the gaps in this framework, for example an emissions standard covering municipally owned power plants, which are exempt from the RPS and CES.

When the Massachusetts legislature passed a bill to restructure the electricity industry in 1997, it also enacted an RPS framework (Mass, 1997). The standard came into effect in 2003 but has been modified a number of times since then, including through the Green Communities Act in 2008 and the Next Generation Roadmap Act in 2021. The RPS requires that an increasing percentage of electricity sold in the state must come from renewable sources each year. Photovoltaic and thermal electric, wind, small hydropower, biogas, marine, and geothermal are all eligible (MassDOER, 2022).

In 2008, Massachusetts enacted its first economy-wide emissions limit through the Global Warming Solutions Act, GWSA (Mass, 2008). A group of residents later filed a lawsuit against the MA Department of Environmental Protection in *Kain v. MassDEP*, arguing that MassDEP had failed to fulfill its obligation to reduce emissions under the GWSA. The Massachusetts Supreme Judicial Court ruled in favor of the plaintiffs in 2016, requiring MassDEP to adopt additional emissions reduction measures (MassSJC, 2016). One of the programs that MassDEP implemented as a result of this lawsuit was the CES. Massachusetts' CES is very similar in structure to its RPS, but the CES sets more stringent targets and includes eligibility for large hydropower. (As of 2018, the most recent year for which data is available, the CES was fulfilled exclusively with resources that were already eligible for the RPS.)

Also in 2016, the legislature passed the Energy Diversity Act, requiring electricity distribution companies to solicit long-term contracts for 1,600 MW of offshore wind capacity (later increased to 5,600 MW) and 9,450,00 MWh/year of other clean energy generation (Mass, 2016). The clean energy generation is likely to be fulfilled with a contract for Canadian hydroelectricity imports, although siting adequate transmission capacity has been challenging; see section 3.2 below. The Energy Diversity Act procurements will overtake the CES and RPS by 2030 unless those standards are strengthened (EEA, 2020).

The RPS, CES, procurements, and related policies make low-carbon electricity projects more financially attractive to energy developers. Once an energy developer identifies a project, they must also secure the necessary land and rights-of-way for the project, often requiring interaction with private property owners near the site of the project. The National Environmental Policy Act (NEPA), one of the United States' first comprehensive environmental protection laws, requires federal agencies to study the environmental impacts of proposed infrastructure projects, as well as assessing reasonable alternatives, before making decisions related to permit approval, land management practices, or the construction of publicly funded facilities (EPA, 2021). Many states have developed similar policies, including Massachusetts, where the corresponding law is the Massachusetts Environmental Policy Act (MEPA). NEPA and MEPA apply to energy projects which almost always need to obtain federal and/or state permits, which are granted by agencies that must complete an environmental review first.

NEPA and MEPA provide agencies with information about environmental concerns, but they do not require agencies to act on that information to minimize impacts. Rather than specifying a certain course of action, two of the most important functions of NEPA and MEPA are to coordinate agencies' actions and provide opportunities for public participation (Estrella, 2008). Because it provides both information and public comment periods, environmental review is often the first stage of community resistance to projects, which may then branch out into other legal and regulatory venues. While public participation is an essential part of infrastructure development and ideally encourages constructive criticism and functional community participation with collaboration and compromise, under current frameworks it often leads to stalemates that slow the pace of clean energy expansion.

3. Local Opposition to Energy Projects

There are a number of social and political dynamics that influence energy sector decarbonization. Recent events in Massachusetts and surrounding states suggest that "energy acceptance," or the willingness of communities to have energy projects sited within their boundaries, is particularly important in determining which low-carbon technologies are rapidly deployable (Wüstenhagen, 2007). (One facet of energy acceptance is a phenomenon known as "NIMBY," or "not in my backyard," when people who are generally in favor of a technology object to it being sited near them.)

This section examines two biomass plants and two transmission projects in New England that met with local resistance. As the following examples demonstrate, siting constraints related to energy acceptance will need to be better understood before they can be incorporated into policy decisions, and ultimately into energy sector modeling, for clean energy initiatives to be effective. The goal of this paper is to emphasize the need to develop the methods and mechanisms to include social dynamics into electric system modeling. As acknowledged in section 7, there are a number of such frameworks. The evidence that existing mechanisms to combine social and technical analyses are insufficient is that society has yet to decarbonize the power sector at the pace required to meet government policies and industry targets. The examples below illustrate common channels through which resistance to energy projects occurs. Understanding these mechanisms is vital for the policymaking process to facilitate the required pace of decarbonization.

3.1. Western Massachusetts Biomass Projects

Most biomass power plants were eligible under the original Massachusetts RPS, so after the standard first came into effect in 2003, there was a burst of interest in biomass throughout the state. Although biomass combustion creates carbon dioxide, the idea at the time was that biomass power plants do not increase net atmospheric carbon dioxide because they use fuel that is already active in the carbon cycle. Later research revealed that biomass plants often have long carbon payback periods, even relative to fossil fuel generation, and biomass eligibility was later removed from the Massachusetts RPS. Even so, the proposed biomass plants in Russell and Springfield described below illustrate some of the common channels for community resistance to energy projects.

Russell Biomass, LLC proposed building a 50 MW power plant at a site that had been used for industrial purposes since 1870, but was abandoned when the Westfield River Paper Company Mill closed in 1995. The permitting process for Russell Biomass began in 2005 and continued until the project was officially canceled in 2012.

Debate over the biomass plant took place at both the state and local levels. At the state level, proponents argued that it would contribute to Massachusetts' renewable portfolio goals as well as lower electricity costs and increase reliability. Within Russell itself, it would have created 22 permanent jobs and increased town tax revenue by thirty percent, but would also have brought heavy truck traffic through the downtown area, and would have affected local air quality and drawn cooling water from the Westfield River, potentially impacting aquatic life.

Although an initial survey completed by Russell Biomass found that about two thirds of respondents thought the benefits of the plant outweighed their concerns (Russell, 2005), construction of the plant became a deeply contentious issue. The plant required 23 permits from a variety of agencies at the local, state, and national levels. Discussions with stakeholders involved with the project suggests that the project was canceled because of extensive public opposition, which dragged out the environmental permitting to the point of being untenably expensive.

A similar biomass proposal in Springfield, MA also failed. Springfield, the third largest municipality in Massachusetts, is a racially and linguistically diverse city. In 2020, the median household income was less than half of the median income for Massachusetts as a whole. Nearly all the neighborhoods in the city meet at least one of the state's criteria for environmental justice populations, which are based on household income, minority population, and English language proficiency.

Community opposition to the plant centered on air quality impacts, which are a leading public health concern in Springfield, frequently referred to as the "asthma capital of the United States" (AAFA, 2018). While project developers insisted that the public health impacts of the plant would be negligible (Gradient, 2010), community advocates argued that any additional air pollution was too much in a city already struggling with respiratory health.

Though not yet cancelled, the project does need to resolve legal challenges, apply for a new permit, overcome local ordinances, and locate financing for the plant. These combined requirements are likely to permanently block plant construction.

3.2. Quebéc-New England Transmission Lines

Although hydroelectricity raises controversies of its own, the plentiful hydropower available in Quebéc has historically provided a valuable source of low-carbon electricity to New England. Expanded use of this resource would require additional transmission capacity, which would also let Quebéc play a role in balancing the grid in New England (EEA, 2020). Over the past decade, there have been two major proposals to build transmission lines connecting Quebéc and New England, the Northern Pass and the New England Clean Energy Connect (NECEC). Both created intense local controversy and neither was constructed, although there is still a chance the NECEC will become operational.

Transmission lines face extensive siting challenges because project developers must assemble a continuous right-of-way along the entire length of a new transmission line before it can be built. This requires obtaining authorization from a large number of governmental stakeholders along the route as well as property rights for the length of the line. The refusal of any one of these parties can bring the entire project to a halt. Other complicating factors include the high costs of transmission and the allocation of costs and benefits between numerous stakeholders (Zevin, 2020).

3.2.1. Northern Pass. The utility company Eversource unveiled its proposal for the Northern Pass, a 192-mile transmission line passing through New Hampshire, in 2010. Transmission line permitting is generally the purview of state governments, but because the Northern Pass crossed the US-Canada border, it also required a Presidential Permit from the U.S. DOE, which Eversource applied for in 2010 and received in 2017 (DOE, 2017).

At the state level, the project required approval from the New Hampshire Site Evaluation Committee (SEC). The majority of the proposed line was sited along existing transmission corridors, but it also required "32 miles of new aboveground right-of-way and 60 miles of underground installation in roads where there [is] no pre-existing…corridor for transmission lines" (NHSEC, 2019).

In 2012, the state legislature forbade using eminent domain for transmission projects like the Northern Pass (*i.e.*, transmission lines that would not be used in New Hampshire (Brnger, 2012)), that required Eversource to individually convince landowners to sell their property.

Meanwhile, fierce opposition to the project had developed in the towns along the route (NHSEC, 2019). New Hampshire residents would have borne most of the project's negative impacts, but because of utility power purchase agreements, they would not have benefited from lower electricity rates offered by the new transmission capacity (Courchesne, 2011).

The need for a federal permit, combined with the potentially large environmental impacts of the Northern Pass, triggered review under the National Environmental Policy Act (NEPA), and this process received notable levels of public participation. Community members also expressed their opposition by hindering Eversource's ability to assemble a continuous right-of-way. A large challenge for Eversource was conservation land in the path of the line. Eversource modified the proposed route of the Northern Pass several times, attempting to circumnavigate these obstacles. Issues with the right-of-way would likely only have slowed the project, but it was blocked entirely by a NH SEC decision in 2018 to deny its application.

The project had taken on direct significance for Massachusetts with the enactment of the Energy Diversity Act, which (among other provisions) required electricity distribution companies in the state to procure 9.4 GWh/year of clean energy (Mass, 2016). In January 2018, the Northern Pass won the bid to supply this electricity, but barely a week later, the New Hampshire SEC rejected the Northern Pass proposal. At that point, Massachusetts switched to a different bidder, the New England Clean Energy Connect (NECEC) (Cunningham, 2018).

3.2.2. New England Clean Energy Connect. The NECEC was a similar transmission project to the Northern Pass, but would have been constructed through Maine rather than New Hampshire. It initially appeared less controversial, and construction began in early 2021. However, resistance to that project also arose, composed of an unlikely combination of environmental groups opposed to forest clearing and nuclear/fossil fuel interests who would have lost money from inexpensive hydroelectricity entering the wholesale market (Turkel, 2021). Opposition to the NECEC culminated in voters blocking the project through a ballot initiative in November 2021. Appeals over the constitutionality of the ballot initiative are ongoing, as are legal challenges to the project from several other angles (Turkel, 2022). If these issues are not resolved by the contractual deadline established with Massachusetts distribution companies (August 2024), it is unclear how Massachusetts will fulfill its clean energy procurement requirements.

3.3. Mechanisms for Community Resistance

Community resistance was a key cause of failure for Russell Biomass, Springfield biomass, the Northern Pass, and the New England Clean Energy Connect. In Russell, friction in the permitting process and numerous design changes made the project prohibitively expensive. Loss of RPS eligibility affected the Springfield plant. Interference with right-of-way development slowed the Northern Pass, and a decision by the NH Site Evaluation Committee permanently blocked it. In Maine, a ballot initiative directly stopped the NECEC. All four projects also became mired in a number of lawsuits filed by community and environmental groups.

These projects reveal several lines of influence for communities to oppose projects. Opposition may increase design costs by slowing the permitting process or interfering with rights-of-way, it may lower project financial viability by changing policy incentives, or it may directly block projects through policy changes or administrative decisions.

Because energy acceptance affects project viability, it will affect the pace of low-carbon electricity infrastructure expansion and will need to be accounted for in policy design. Though the examples of local opposition discussed here are not focused on wind or solar installations, as in the modeling examples of section 5, the modeling frameworks, and often the actual power system models themselves, are the same as what would be used to analyze biomass installations and transmission expansion for hydro-electric facilities. The point emphasized in this paper is that, like other social factors that influence infrastructure decisions, energy acceptance is omitted from current power sector models. This raises questions about the types of information existing models can provide to inform policy design, and whether social constraints can be incorporated into power sector modeling.

4. Power Sector Modeling for Policy Design

4.1. Strengths and Weaknesses of Modeling

The process of designing effective and equitable power sector decarbonization policies requires analysis of an array of questions about potential system and societal impacts. Policymakers must balance the pace of increasing renewable requirements with maintaining system reliability, decide which fuel sources to encourage for minimizing electricity costs, and realign the distributional impacts of policies.

Because there is limited empirical data on deep decarbonization in the power sector, these questions are typically investigated with computer models. The models are usually techno-economic models that solve for least-cost pathways subject to technical constraints, assuming that system behavior is determined by rational, perfectly informed individuals. An example of this type of modeling framework is presented in section 5 below, examining the potential for VRE projects in Massachusetts.

Power sector models generally have very limited representation of the social and political forces that interact with technological change, but an energy transition that touches every aspect of society will clearly be affected by social and political forces as well as technical and economic ones. The techno-economic modeling tradition grew out of the oil crisis (Pfenninger et al, 2014), when the focus was on maintaining energy security and lowering costs, not on spurring a society-wide transformation to a decarbonized power sector. While these modeling frameworks have provided valuable analyses for decades, the urgency of today's climate crisis requires a broader and transformed modeling framework that is best-suited for climate policy design.

Techno-economic power sector models do provide two main areas of important insight for policy design. First, they provide details of physical constraints on grid operation. Understanding the range of technically viable decarbonization options is an essential first step to policy design. Second, models give indicator assessments of policy options, allowing for the policies to be ranked on criteria such as cost, tons of carbon emissions, land use, and system reliability.

There are also two categories of important information that current power sector models are incapable of producing. First, models cannot identify socially optimal projects. Though this statement contradicts the economic foundation of the traditional techno-economic modeling framework for power systems as well as the general equilibrium modeling framework, the increase in local resistance to energy projects demonstrates that the social optima as modeled does not adequately capture society's actual valuation of the projects and their impact on daily life. Models can optimize quantifiable values (*e.g.,* cost), and can inform tradeoffs between policy options, but identifying a socially optimal pathway is outside their scope. "*Mathematical models are a great way to explore questions. They are also a dangerous way to assert answers. Asking models for certainty or consensus is more a sign of the difficulties in making controversial decisions than it is a solution, and can invite ritualistic use of quantification*" (Saltelli 2020, p. 484).

A second critical shortcoming of existing models is their inability to calculate the *achievable pace* of clean energy expansion. Decarbonizing the power sector to meet climate deadlines will require an unprecedented pace of infrastructure change. A variety of factors not traditionally included in techno-economic models impact the pace of change, including local opposition, financing barriers, and industry culture.

Techniques exist for using models in policy-making, by accounting for unmodeled values and behaviors exogenously. One such method is to build upon scenario analysis to capture a range of potential system parameters and future events. In analyzing offshore wind in Massachusetts, one study used a scenario that constrained offshore wind to illustrate the impact of widespread resistance to turbine construction (EEA, 2020a). To represent the political influence of the natural gas industry, a scenario with low electrification of gas end-uses was developed. Other modeling options include multi-attribute tradeoff analyses and Monte Carlo modeling, involving many tens of thousands of scenarios to provide a wealth of information to analysts and decision makers. The effectiveness of scenario analysis for informing the pace of clean energy expansion is limited though simply because not everything can be quantified or represented as a parameter or variable for a given modeling framework.

4.2. Modeling Social Dynamics

Efforts to include social and political dynamics in power sector models will benefit decision-making. The question is whether the social dynamics affecting power sector decarbonization actually can be modeled, or whether they are fundamentally different from technical and economic constraints. What is an underlying reason that approval of power system projects does not follow a least-cost pathway? Four main categories that explain this divergence are: externalities, concentrated interests, local variability, and social and political institutions.

4.2.1. Externalities. For energy infrastructure, relevant externalities often include greenhouse gas emissions, air and/or water pollution, and land use considerations. In theory, it is simple to include externalities in power sector models by assigning monetary values to benefits and harms that are unpriced by markets. However, it is difficult to calculate the monetary value of health and environmental benefits in a consistent way. Methods to estimate prices for benefits such as reduced air pollution (or for corresponding harms like increased pollution) are usually oversimplified and incomplete (Ackerman and Heinzerling, 2002). Pricing externalities may still be useful in some circumstances, but value judgements will always need to be made outside of models. Various frameworks exist for using model output to inform these judgements. For example, multi-attribute tradeoff analysis is a technique for comparing options without needing to translate non-cost values into monetary units.

4.2.2. Concentrated Interests. Climate benefits are inherently decentralized, while negative impacts are often localized. Unless incentives are properly aligned, a community may—often quite rationally—not be willing to make sacrifices for broader climate goals. Modeling this type of rational, localized resistance would be useful in that it could identify areas where policy solutions are needed to alter the distribution of costs and benefits and increase the social feasibility of energy projects. With new techniques to appropriately represent distributed global effects versus concentrated local effects, bi-level modeling could be employed to represent and analyze the disjunction between populations that enjoy the benefits of clean energy project and those that bear the majority of the costs.

4.2.3. Local Variability of Constraints. Technologies beneficial in the abstract may not be acceptable in reality at local levels. A passionate advocate may live near a proposed project (Russell Biomass), or local ordinances may affect energy projects (Springfield biomass plant). Local laws also frequently impact wind and solar development. Opposition along a desired right-of-way and ballot initiatives were seen to block transmission expansion (Northern Pass and NECEC). These effects cannot be modeled, because by definition they do not follow a generalizable pattern that can be represented with an equation. And though power sector models are not intended to predict the success or failure of individual projects, the influence of energy acceptance factors are already affecting power system transition. Though possibly problematic due to their obscured algorithms and frequent biases, neural network models could be employed to better predict local variability and the impact on clean energy projects.

4.2.4. Social and Political Institutions. To improve the quality of information for policymakers, models will need to incorporate policy constraints beyond the typical tax incentives and carbon pricing. There are aggregate behavioral patterns that cause nonlinear behavior in real systems, including public opinion, trust in political institutions (Peng, 2021), conformity to social norms, interest group formation, and perceptions of climate change (Moore, 2022), that have yet to be sufficiently represented in energy sector modeling. Among modelers, there is growing interest in finding better ways to incorporate knowledge from the social sciences into the modeling process. Analysis so far has often focused on integrated assessment models, but similar reasoning applies to power sector models as well (Pfenninger et al, 2014; Süsser et al, 2022). The modeling tractability and usefulness of including these dynamics varies widely by context.

5. Development of Example Model

A specific example of power system modeling with increasing VRE is presented next. This type of modeling effort is often intended to inform policies designed to promote clean technologies. The model and dataset discussed here are simpler than many that are used by researchers and industry, yet serve to raise issues that are common throughout power sector modeling. As discussed in Section 4, such apparently straight-forward modeling often fails to promote clean energy projects.

This section outlines a model of the New England power system (Metz, 2022) developed from sources including ISO-NE, the U.S. EIA, NERC, and NREL. A 15-bus representation of the New England electric grid was designed (Metz, 2022) based on transmission line geography (ISO-NE, 2020a; EIA, 2021b) and an existing ISO-NE hub and spoke model (Coste, 2016). Each county was assigned to a bus, and total regional real power demand (ISO-NE, 2020b) was apportioned to the buses by assuming that electricity consumption is proportional to population. Similarly, generators were assigned to buses based on their county-level location.

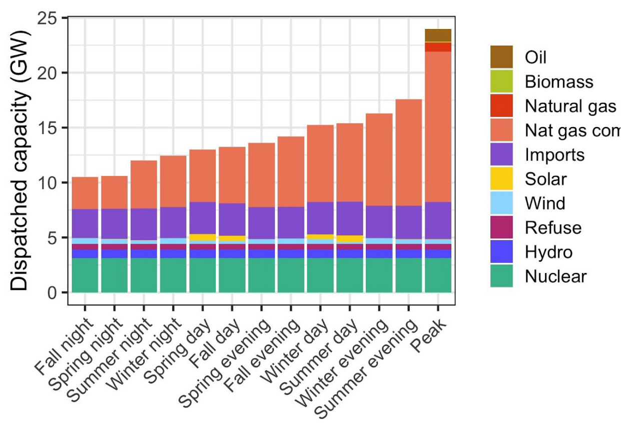

Figure 1: Representative hours for ISO-NE

To capture the range of supply and demand conditions that the system experiences throughout the year, a set of thirteen representative hours was developed, figure 1, using an adaptation of the method from NREL's ReEDS model (Brown et al, 2020). Each representative hour is specified by a load level, wind and solar availability factors, and a frequency (the proportion of the year for which that representative hour describes the system). To determine the load in each representative hour, hourly load data from ISO-NE was sorted into the thirteen time categories, and the median value from each was taken as the representative load. The availability factor of wind and solar during each representative hour was determined from the System Advisor Model (NREL, 2020). Levelized generator costs were obtained from the EIA (EIA, 2021a).

The computer simulations were run using Matpower OPF (Zimmerman, 2011).

6. Analysis of modeling results & capabilities

6.1. Calibrating the base case

This section examines the strengths and weaknesses of the model for analyzing power sector decarbonization, including both the mathematical representation of power system operations and the input dataset developed for the New England power grid. This discussion serves as a representative case study for similar analyses of power system performance with new technologies, that are similarly intended to prove the value of new projects. A theme in this paper is the concern that this traditional framework of computer modeling, when used to promote decarbonization projects, has systemic flaws which undermine the success, within society, of otherwise technically viable system expansion projects. The relative simplicity of this model does not negate the pressing issues raised here about techno-economic modeling,

Table 1: Accuracy of modeled annual resource mix

Generator Type	Modeled value	Actual value (2019)	Difference
Renewables (excl. hydro)	8.4%	9.4%	-1.0%
Hydro	5.5%	7.4%	-1.9%
Nuclear	23%	25%	-2%
Natural gas	42%	40%	+2%
Net imports	21%	19%	+2%
Oil and coal	<1%	<1%	—

An important first test of validity for the modeling effort is how well the model reproduces current system operation. The modeled annual resource mix closely matches the actual New England resource mix, as shown in table 1, demonstrating that the model developed here reasonably reproduces real system behavior for generator dispatch.

6.2. Increasing penetration of solar PV

Solar PV was added to the system in increments of 3GW, and the annual resource mix was calculated for each level of solar capacity (figure 2). An increment of 3 GW clearly shows changes in the resource mix while not requiring an excessive number of model iterations. As seen in figure 2, initially the solar capacity displaces natural gas generation, lowering the system emissions intensity. With low operating costs, solar also partially displaces nuclear generation and imports, as well as wind and hydro (though this would be unlikely to occur in reality). Above 35 GW, additional solar capacity no longer displaces other generating resources suggesting that without the addition of complementary resources such as storage, solar cannot meet more than 45% of current system load. For policy makers, tracking the effects of 3GW increments of solar PV, and identifying a maximum possible penetration level could be useful to promote this type of power system modeling.

Solar PV can be installed as roof-top, or other configurations close to load centers (such as along highways), and so avoid the need for transmission system expansion. Yet no power system, including the New England, will be decarbonized through solar construction alone. The effect of pairing solar with onshore and offshore wind is examined below.

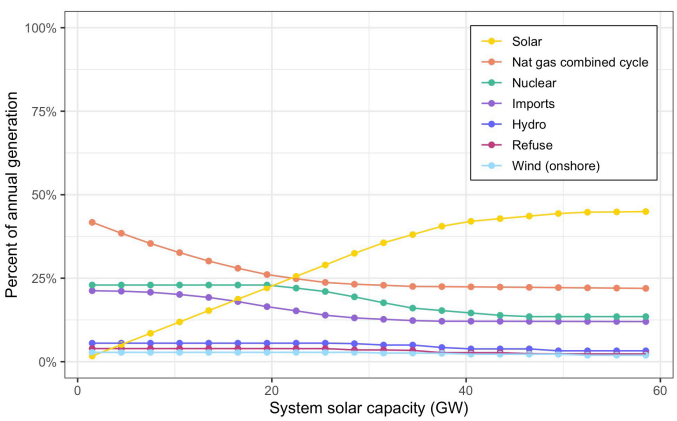

Figure 2: Resource mix with increasing solar capacity.

6.3. Effects of pairing solar and wind

New England has the potential to construct both onshore and offshore wind capacity. The resource potential of offshore wind is particularly large, but to date the only operational offshore wind farm is 30 MW in Rhode Island. The remaining 1,360 MW of existing New England wind capacity is located onshore.

Matpower simulations confirm that wind is capable of serving a much higher fraction of the load than solar because wind does not have the dramatic diurnal cycle that solar does, so it is better suited to serving evening loads.

Figure 3 shows results for the combined benefits of pairing wind with solar energy. As a starting point, each gigawatt of renewable capacity added to the system is 50% onshore wind and 50% solar. Together, the solar and wind are able to serve over 85% of annual load on the system. Results are similar using offshore wind. Note that wind installations typically require transmission system expansion, while solar PV is less likely to do so.

The results presented here for pairing wind and solar, are the type of results often offered to policy makers for developing climate related energy policies.

For reasons discussed above, society and industry have yet to embrace such projects necessary for an energy sector transition, even with abundant modeling results and analyses that seem to prove their significant benefits.

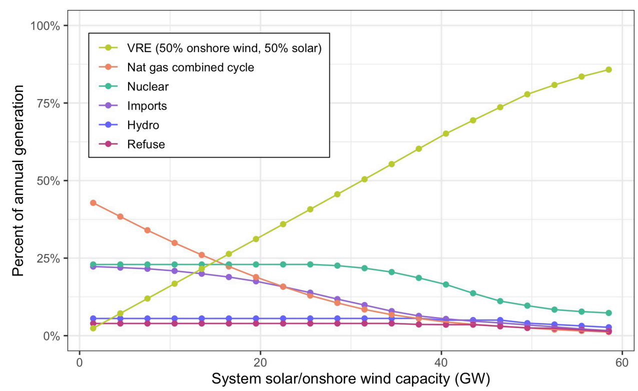

Figure 3: Modeled resource mix as both solar and onshore wind capacity increase.

6.4. Limitations and future model development

This model of the New England electric grid, as well as other similar models, is useful for illustrating general system behavior that will emerge as the level of VRE increases, but there are a number of limitations that must be addressed before such models will be suitable for a full examination of the tradeoffs between technical and social interests. Consistent with many power systems studies, the limitations of the model used here include the level of spatial detail, algebraic reduction techniques, lack of chronology in the representative hours, limited selection of technologies, and simplified cost data.

These limitations apply to many studies and are increasingly problematic as engineering-focused models are used to inform policy design. The limitations of the large-scale computer models are of particular concern for small-scale, local project decisions that are the bedrock of high-level climate focused energy policies. At a pragmatic level, high resolution, local data is often not available. Overall data availability is a major constraint to the level of detail in most models, and so limits realistic results that could be meaningful to inform policy design and decision-making. Limitations from temporal detail and chronology in data also play an important role.

However, even if these and more data limitations were addressed to allow for more complete system modeling, the analyses would omit important social constraints on clean energy expansion.

7. Conclusions

The nation and the planet need stronger clean energy policies in order to supply enough low-carbon electricity to meet greenhouse gas reduction targets. These policies need to be designed to move the energy system to net zero emissions while maintaining priorities such as reliability and affordable consumer energy prices, and also to do so at a rapid pace. One of the main technical challenges that the grid faces under deep decarbonization is interconnecting significant VRE technologies while maintaining high system performance. Power system models excel at identifying grid expansion options with high VRE penetration and high reliability. However, lack of energy acceptance within society prevents implementation of such options.

Resource diversity, overbuilding, demand response, short-term storage, and firm generation will all help balance supply and demand in systems with high levels of renewable energy, and lead to a range of technically feasible decarbonized resource mixes. This paper emphasizes that the actual feasible range of solutions is significantly narrower than the technically feasible range because of constraints related to social and political factors, including energy acceptance.

Even the most beneficial infrastructure developments come with tradeoffs. At the local level, a project may bring tax revenue and jobs but may also disrupt land use or create air, noise, and water pollution. This leads to community resistance to infrastructure projects. Fortunately, most low-carbon technologies produce significant co-benefits, but especially difficult conflicts arise when a project with negative local impacts supports the large-scale policy goals of reducing greenhouse gas emissions.

Opposition to energy infrastructure slows clean energy deployment, so one part of decarbonizing the power sector will be to effectively engage with communities to increase energy acceptance. Opposition often highlights legitimate issues with proposed projects, and overcoming it will require protecting environmental justice communities and preserving wilderness areas as clean energy infrastructure expands. Within Massachusetts, the consistent failure of certain types of large-scale projects means that the most feasible solution to the balancing challenge may be more skewed towards distributed technologies than the least-cost solution would imply.

As well as illustrating the specific challenges of power sector decarbonization in Massachusetts, the case study presented above illustrates the strengths and weaknesses of power sector modeling as a tool to inform climate policy design more generally. Modeling is useful for identifying technically feasible options and for comparing them based on quantifiable indicators, usually with an emphasis on cost. Models are generally incapable of solving for socially optimal solutions and estimating achievable pace of decarbonization.

There is room for human behavior and social institutions to be more accurately included within models, but many social factors are not yet incorporated into power sector models effectively. These factors are often accounted for exogenously, through scenario design, stakeholder engagement, and iteration with other types of social science analysis.

To better inform decarbonization policy-making, power system researchers need more effective methods to account for all the constraints on clean energy expansion—technical, economic, social, and political. Solutions do not lie within our existing modeling frameworks, not even those that explicitly involve stakeholder interactions, or embrace a general equilibrium method. These have all been proven insufficient for the task of decarbonizing the power sector at the necessary pace by the simple observation that we are not making sufficient progress on decarbonizing efforts. Solutions will come from analysis frameworks that are developed with the *primary* intent to be that of informing decarbonization policies. This problem is looming over all facets of life on Earth, and must be engaged by our full community of energy researchers, professionals and advocates. Otherwise, we will fail to enact and implement ambitious enough policies and fail to achieve our climate goals.

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