Technology Review for Carbon Neutrality

Perspective

Toward more transparent, high-resolution, stakeholder-engaged energy-transition decision-support modeling

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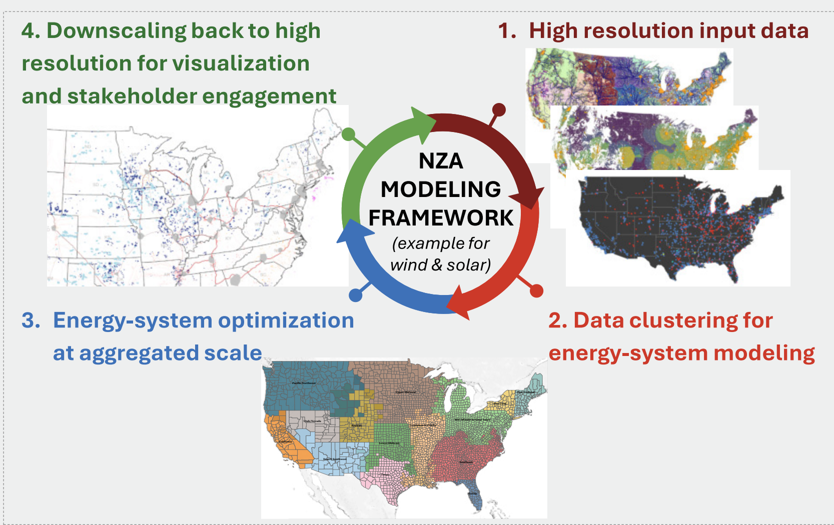
Received: 04 December 2025
Revised: 24 December 2025
Accepted: 24 December 2025
https://doi.org/10.26599/TRCN.2025.9550022

ABSTRACT

Improved modeling approaches to support decision making are needed to help accelerate the transition to low-carbon energy systems. We offer insights into improving energy transition decision support modeling, drawing on our experience with the Net-Zero America (NZA) project and analogously designed ongoing projects led by researchers in Australia, Brazil, China, India, Republic of Korea, and Poland. The NZA study was impactful because of 1) uniquely high spatial, temporal, sectoral, technological, and socio-economic modeling and visualization using objective, transparent, and scientifically rigorous methods and 2) complementary policy-actionable bridging analyses informed by transparent and unusually extensive engagement with a broad set of stakeholders. The NZA approach established a new standard for high-resolution energy-transition decision support modeling, but further improvements in methods and tools are needed. A foremost need is improving optimization modeling so that it better reflects on-the-ground realities and risks associated with efforts to deploy energy technologies and infrastructure at the scales and pace needed to achieve mid-century net-zero emissions goals.



Improved modeling approaches to support decision making are needed to help accelerate the transition to low-carbon energy systems globally. We offer insights into improving energy transition decision support modeling based on our experience with the Net-Zero America (NZA) project and analogously designed ongoing projects in Brazil, China, India, and elsewhere.

KEYWORDS

Macro energy systems; energy transition modeling; Net Zero America

1. Introduction

Global integrated assessment models (IAMs) have long played a key role in shaping society's understanding of the energy-climate-economy-land interactions[1] and in informing global long-term policy goals, such as the climate targets embodied in the Paris Agreement, and the assessment of nationally determined contributions. However, coarse spatial and temporal resolution often makes global IAMs insufficient for addressing the practical dimensions of energy investments and decarbonization implementation, such as issues of feasibility, sequencing, and administrative capacity. Insights into such issues are critical for the design of effective national or subnational decarbonization policies and implementation plans, and for guiding large-scale infrastructure investments. In contrast to IAMs, optimization-based planning models[2] focus on the design and operation of energy systems at national or subnational levels and provide for higher spatial, temporal, sectoral, and/or technological resolution that can help better understand feasibility, support policy design, and steer planning and implementation actions. Nevertheless, computational tractability considerations limit the resolution at which planning models can be run. Improved energy transition decision support modeling approaches are thus needed.

In this context, a new field, Macro-Energy Systems (MES) is emerging[3,4], the aim of which is to help better understand the dynamics, benefits, costs, impacts and implementation challenges of large-scale (e.g., national) energy systems and energy system transitions by drawing on the best open-source energy system planning models[5] and cross-disciplinary analyses incorporating methods and tools from engineering, business, public policy, and other social sciences. In this article, we offer our insights into further MES development to improve energy transition decision support efforts, drawing on the experience of three of us with the Net-Zero America (NZA) project[6,7] and analogously designed ongoing projects the four of us are involved with in collaboration with local researchers leading the efforts in Australia[8], China, India, Brazil, Poland, and Republic of Korea. Princeton-catalyzed "Net-Zero X" (NZx) projects in additional countries are under discussion (Fig. 1).

For NZA, a project team of 18 researchers with a variety of disciplinary backgrounds across nine different institutions collaborated to model alternative technological pathways to net-zero greenhouse gas emissions for the United States by 2050[6]. The study attracted an unusually high level of attention from a wide range of government, private-sector, and civil society stakeholders and helped move the U.S. decarbonization effort forward in important ways, including shaping the development of landmark federal climate legislation[9,10]. More than four years after its release, the NZA study continues to be widely cited in discussions of U.S. energy transitions. While U.S. climate change mitigation progress has slowed since a change in government, the NZA effort nevertheless demonstrated the effectiveness of the modeling approach in providing decision support, including agenda-setting for policy making and identification of new priorities for planning and policy intervention. The study drew international attention and led to the launching of similarly-designed NZx studies in other countries (Fig. 1).

The NZA study was impactful because of two notable features: 1) uniquely high spatial, temporal, sectoral, technological, and socio-economic modeling and visualization using objective, transparent, and scientifically rigorous methods and 2) complementary policy-actionable bridging analyses informed by transparent and unusually extensive engagement with a broad set of stakeholders from early on in the work through the full two-year study period and beyond.

2. High-resolution modeling and visualization

The NZA study sought to provide policy-actionable answers to the question, "What energy and industrial technology deployments would transition the U.S. economy to net-zero emissions by 2050, and what would be the implications for natural, manufactured, financial, social, and human capital of following such pathways?" The NZA researchers first modeled, at coarse spatial resolution (14 regions nationally), several technological pathways to net-zero emissions by 2050, each cost-minimized under different sets of constraints to reflect inherent future uncertainties around geophysical limitations and different stakeholder perspectives on the composition of "the best" transition pathway. The thoughtful design of constraints to create qualitatively distinct decarbonization scenarios helped stakeholders on different sides of energy issues find common ground, or at least better understand trade-offs involved in following different pathways. Moreover, the scenarios were policy-neutral, i.e., the pathways objectively described the sequence of least-cost plant and infrastructure deployments that

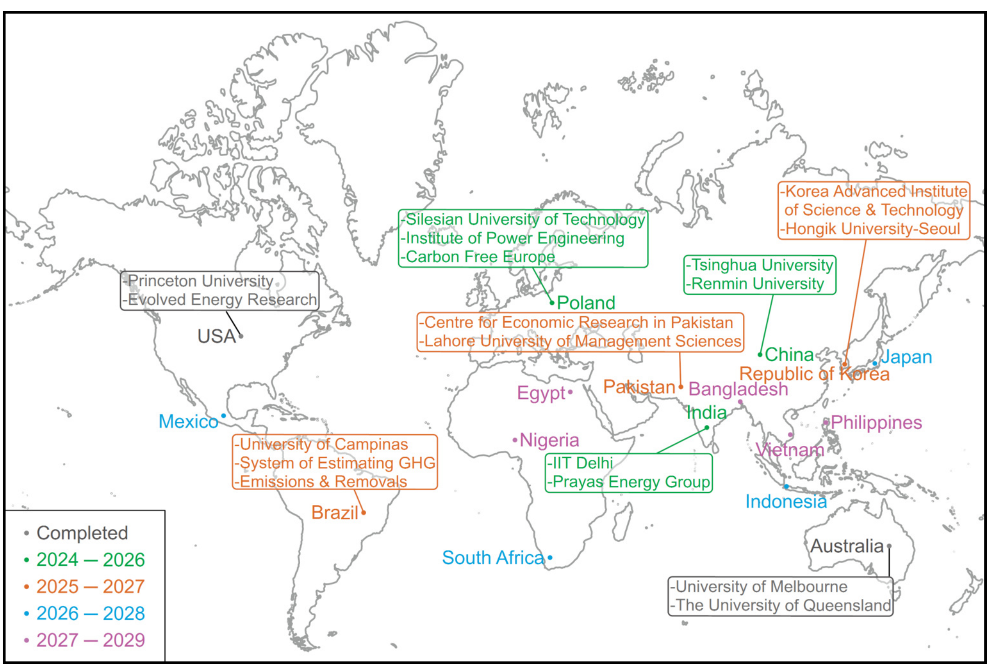


Fig. 1. Countries, and associated local research-team leads, where initial Net-Zero X studies have been completed or are ongoing in collaboration with Princeton researchers, and additional countries where similar NZx studies are contemplated.

would achieve the net-zero goal without reference to any policies needed to achieve it. The objective was to inform policy priorities and agenda setting but not prescribe or evaluate specific policy interventions. The challenges of meeting the emissions goal differed significantly between the modeled pathways (Fig. 2(a)), as did prospective impacts on the five capitals (Fig. 2(b)). The NZA team took no position on which modeled pathway was "best" or "preferred," considering that all achieved the 2050 net-zero goal, and each entailed significant implementation challenges and salient tradeoffs.

The NZA study then brought the scale and speed of change implied by the pathways to life, by *downscaling* the most significant categories of energy supply and industrial decarbonization assets required for the transition using geospatial mapping methodologies pioneered and further refined by others, e.g., Refs. 11, 12, and 13. For NZA this involved, for example, identifying candidate project areas (CPAs) across the U.S. at 4 to 8 km resolution for solar PV and wind farms and associated transmission requirements, considering resource availability, quality, and costs, along with spatial exclusion criteria like population density, topography, soil quality, current land uses, and social, cultural, and environmental factors, among others[14]. A subset of CPAs was then identified to meet the generating capacity requirements determined by the coarser resolution modeling (Fig. 3(a)). In turn, such mapping provided critical input for high-resolution exploration of implications for land use, capital deployments, air pollution/health impacts, and employment (e.g., Fig. 3(b)), i.e., impacts of concern to many stakeholders, including national, state, and local policy makers, private investors, and organizations across society. Ultimately, detailed site-specific techno-economic assessments are needed to determine the feasibility of any specific project, but the downscaling work in the NZA study offered unique insight into the aggregate impacts and provided context for individual project assessments.

The computationally tractable, but coarse spatial resolution modeling generated least-cost energy and industrial technology pathways to give big-picture understanding of the scale and pace of plant and infrastructure development required for a net-zero transition. The downscaling allowed stakeholders to visualize the transitions at local scales, and together with complementary bridging analyses, offered visceral perspectives on the implications for natural, social, human, financial, and manufactured capital. In essence, these approaches painted visions of the future at scales sufficiently resolved to potentially guide more grounded, effective policy and decision making and surface important priorities for policy intervention.

Given deep uncertainties about the feasibility of any long-term transition pathway, the NZA work concluded by identifying eight key priorities for action in the 2020s that would maximize optionality and increase the viability of all modeled pathways: 1) Strengthen societal commitment, investment environment, and delivery capabilities; 2) Improve end-use energy productivity and efficiency; 3) Electrify energy demand, especially transportation and buildings; 4) Decarbonize and expand electricity; 5) Prepare for major expansion and transformation of the bioenergy industry; 6) Build infrastructures: electricity transmission

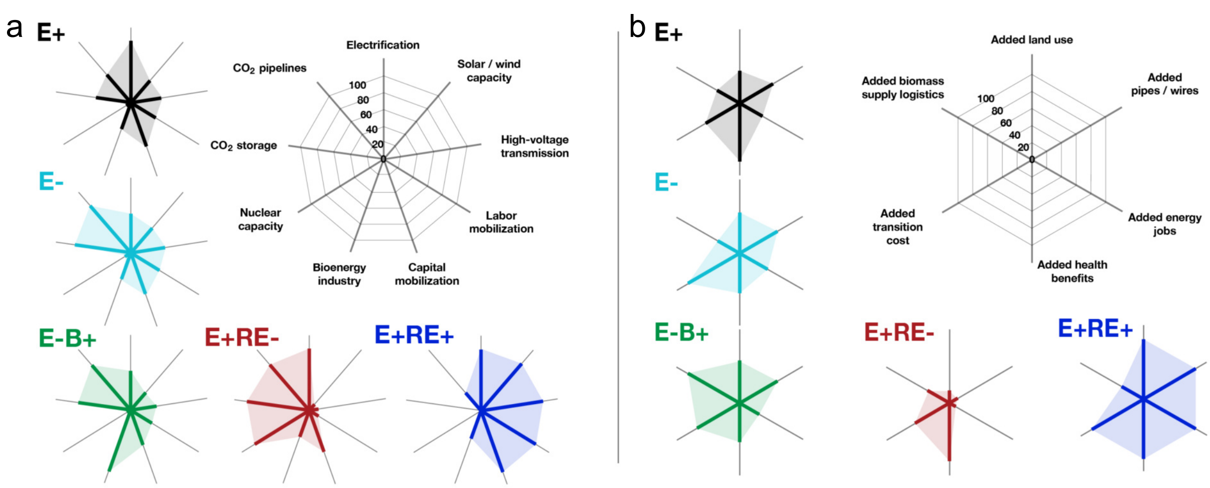


Fig. 2. Ordinally-ranked features associated with natural, manufactured, financial, social, and human capital for different energy-system transition pathways to net-zero greenhouse gas emissions by 2050 in the NZA study based on Ref. 6, including (a) key challenges and (b) impacts. Five distinct technological pathways were developed: E+ = aggressive electrification of energy uses, E- = less-aggressive electrification, E-B+ = less-aggressive electrification and higher biomass supply availability, E+RE+ = aggressive electrification and 100% renewable energy supply by 2050, E+RE- = aggressive electrification and constrained renewable energy supply. The distinct shape of the "spider web" for different pathways implies trade-offs between them.

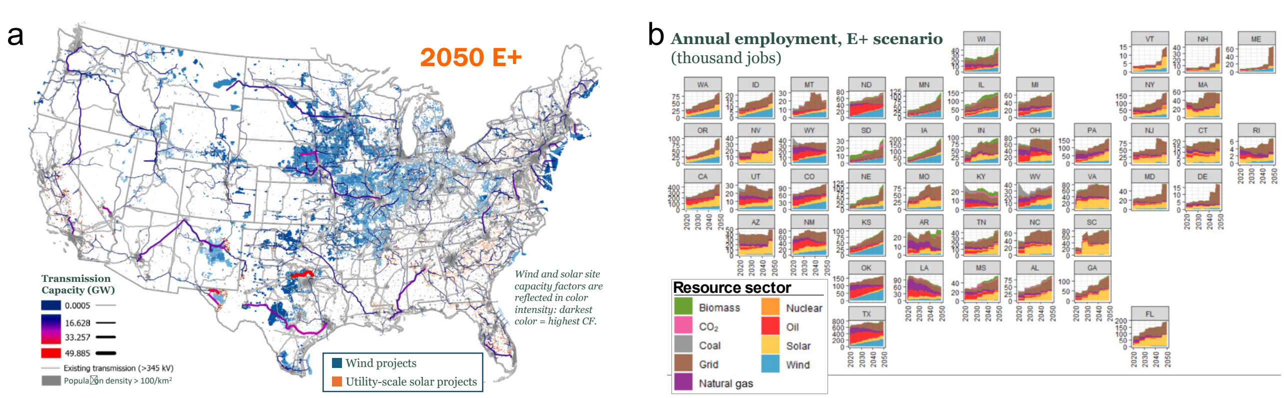


Fig. 3. For one modeled decarbonization pathway this figure shows (a) downscaled mapping (4–8 km resolution) of wind and solar electricity generating projects required by 2050 and (b) estimated annual employment by energy supply resource sector in each of the lower 48 U.S. states from 2020 to 2050. Reproduced with permission from Ref. 6, © Princeton University 2021.

and CO_2 transport/storage; 7) Enhance land sinks and reduce non-CO_2 emissions; and 8) Invest in innovation and demonstrations of pre-bankable technologies to create additional real options that might be needed post-2030. The study also quantified the incremental capital investment needed in the 2020s (above and beyond a least-cost, no-climate-policy BAU pathway) in each of several key areas—electricity, networks, vehicles, buildings etc.—to help anchor policy makers to the scale of intervention required to put the United States on a viable path to net-zero by 2050. This focus on "no-regrets" interventions with high value across multiple potential pathways helped build confidence in a set of policy priorities and proved influential in establishing goals for policy intervention and stakeholder planning.

3. Extensive engagement with stakeholders

Complementing the rigorous, high-resolution modeling, visualizations, and bridging analyses, NZA researchers engaged deliberatively and reflectively with a broader array of stakeholders than is typical (in our experience) for academic decision-support modeling. Concerted and transparent information sharing with a broad cross-section of stakeholders began early, as the study was being framed and developed. Engaging widely with stakeholders in relation to approaches, methods, and key assumptions underpinning the work as it progressed, and soliciting their input on framing scenarios to implicitly capture key uncertainties and different stakeholders' perspectives was a key element of the work. It provided NZA researchers with informed perspectives to help design scenarios, and it helped build trust that facilitated focusing further stakeholder engagements after release of results on the insights generated, rather than on disagreements about assumptions and methods. After release of results, and responding to stakeholder requests, the project leaders gave hundreds of individual briefings on project findings tailored for audiences in government, environmental NGOs and other civil society organizations, private energy and infrastructure companies, financial institutions, and many others. This broad engagement was critical to stakeholders' understanding of the findings and to the impact of the study on public policy and private investment decision making. Interest in the work extended internationally, including from the media[15], and led to the launching of collaborations between Princeton researchers and local teams in other countries to develop similar studies for those countries, as noted earlier.

The NZA effort demonstrated the decision support value to policymakers, companies, and other organizations offered by rigorous, objective, high-resolution energy transition modeling, coupled with applied, deliberative analyses informed by unusually extensive engagement with a broad set of stakeholders. To facilitate ongoing decision support beyond the initial work, the NZA modeling methods and tools were further refined and automated to enable future modeling runs to be made rapidly when needed, e.g., as technology development or policy outlooks evolve over time[16]. A shortcoming of the NZA work, however, was the reliance on a proprietary (non-open-source) energy-system optimization model, which limits the potential for others to use the code for similar studies, including in other countries. With an interest in helping to build similar capabilities for energy-transition decision support modeling globally, Princeton researchers, in collaboration with colleagues at the Massachusetts Institute of Technology (MIT), New York University (NYU), and elsewhere, have been developing a flexible and high-performance energy and industrial-systems planning model, MacroEnergy.jl, released as an open-source software package in 2025[17,18]. This collaborative group of researchers has also made substantial recent advances in the underlying computational methods required to solve large-scale planning models[19-22], opening new possibilities for MES modeling and energy transition studies. MacroEnergy.jl is now starting to be used and tailored for local contexts in the Net-Zero Brazil, Net-Zero China, Net-Zero India, and Net-Zero Republic of Korea studies.

The multiple ongoing NZx projects are creating a global community of researchers sharing and improving NZA-inspired modeling tools and methodologies and tailoring bridging analyses and deliberative stakeholder-engagement approaches to their local contexts. A key value for stakeholder engagement in these studies is local project leadership, which helps assure that the analytical approaches and findings are grounded with local values and norms and also provides the foundation for ongoing decision support beyond the initial NZx effort. While each NZx project is employing the same high-resolution, open-source modeling tools and anticipating extensive engagement with stakeholders, the qualitative design of decarbonization scenarios is necessarily being tailored to the local context.

For example, India is a rapidly developing country likely to experience profound, yet highly uncertain changes in the coming decades in economic structure, urbanization, industries, transportation modes, employment, and livelihoods. Accordingly, the NZ-India study is adapting a scenario design approach originally pioneered for corporate strategic planning by Shell[23]. The approach involves constructing different narratives around key real-world uncertainties and tying quantitative modeling input assumptions to the narratives. The key challenge in this context is to identify feasible decarbonization paths that can deliver on India's development priorities in the face of large uncertainties. For Brazil, where land-use change and agriculture dominate national emissions today, scenario design must integrate land-use and energy/industrial considerations. For example, given bioenergy's large role in the energy system of Brazil today, scenarios will need to explicitly consider the competition for land between biomass energy feedstock production and other uses.

4. Conclusion and future directions

As the need for deep and rapid reductions in greenhouse gas emissions has grown more urgent in recent years, national and corporate pledges to achieve net-zero emissions by mid-century have proliferated. Many such commitments have been given legitimacy by energy modeling studies that describe net-zero transition pathways but provide limited practical insights into implementation feasibility. We call, as others have in varying ways[24-28], for improving decarbonization decision-support modeling, including for many developing countries where such modeling has been especially lacking[29,30]. We argue that open-source spatial, temporal, sectoral, technological, and socio-economic modeling and visualization at politically and societally relevant scales of resolution are essential elements of improved approaches. The high-resolution modeling approach adopted in the Princeton-catalyzed NZx initiative represents a significant step forward in this regard. While improved modeling and visualization techniques are important, complementary bridging analyses informed by deliberative and inclusive engagement with a broad set of stakeholders are equally critical. Such stakeholder engagement should start early and include diverse actors variously engaged in effecting the transition or impacted in different ways by it: local communities, energy asset owners and project developers, project delivery contractors, equipment suppliers, minerals and materials suppliers, financial institutions and capital providers, policy makers, regulators, labor unions, NGOs, indigenous peoples, educators, and others.

The NZA/NZx approach establishes a new standard for high-resolution energy-transition modeling, analyses, and communication in support of policy and decision making, but further improvements in methods and tools are needed. A foremost need in our view is improving optimization modeling so that it better reflects on-the-ground realities and risks associated with efforts to deploy energy technologies and infrastructure at the scales and pace needed to achieve mid-century net-zero emissions goals. The realities include myriad challenges and risks with project development and execution[31], restrictive capital discipline protocols of corporations[32], and potential unintended consequences that can accompany such rapid change. Models to date, including the models currently in use in NZx projects, generally determine least-cost pathways to meet assumed energy and materials demand trajectories, with a specified price on carbon emissions or specified emissions reduction trajectory. Historically, these modeling efforts rely on exogenous assumptions about future costs, employ scenario-based planning with perfect foresight within each scenario, and give insufficient consideration to competition for resources such as land, biomass, water, labor, or minerals. They also assume perfect coordination across sectors and frictionless allocation of capital and resources. *Downscaling* results from large-scale planning models in the NZx projects is designed to bring feasibility challenges and risks into sharp relief, but finding ways to represent these *within macro-energy systems models themselves* would represent a material advance in modeling for energy transition decision support. Some efforts have started to endogenize some real-world factors[33,34], but additional efforts are needed.

Acknowledgements

None.

Author contribution statement

Chris Greig: Writing – review and editing. Jesse D. Jenkins: Writing – review and editing. Eric D. Larson: Conceptualization, writing – original draft, Writing – review and editing. Wei Peng: Writing – review and editing. All authors have read and approved the final manuscript.

Data availability

Not applicable.

Use of AI statement

None.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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