One Earth

CellPress

Commentary

Coupling net-zero modeling with sustainability transitions can reveal co-benefits and risks

Enayat A. Moallemi,[1,*] Michael Battaglia,[1,2] Jody Bruce,[1,2] Stephen Craig,[1,2] Amro M. Farid,[1,2] Lei Gao,[1,2] Andy Hall,[1,2] Peat Leith,[1,2] Larelle McMillan,[1,2] Duy Nong,[1,2] Russell M. Wise,[1,2] and Stuart Whitten[1,2]
[1]The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia
[2]These authors contributed equally
*Correspondence: enayat.moallemi@csiro.au
https://doi.org/10.1016/j.oneear.2024.01.009

Energy modeling underpins the design and deployment of net-zero energy systems. However, many net-zero energy solutions, such as bioenergy and battery storage, are not fully sustainable, and energy models do not adequately account for their sustainability side effects. Here, we identify the scale and scope of challenges and opportunities in consolidating sustainability impacts into net-zero transitions through modeling.

The world is rapidly depleting the carbon budget for limiting global warming to 1.5°C. The deadline for 2030 Agenda for Sustainable Development is also imminent. A transition to a net-zero energy system, coupled with the reconfiguration of the economy and a societal transformation, is needed in less than 10 to 20 years to achieve these connected goals of global sustainability and climate change mitigation.

Models of energy planning and integrated assessment have become the analytical backbone of the policy landscape for transitions to a sustainable, net-zero emissions future.[1] They play a pivotal role in the evaluation of alternative pathways for government policymaking and business decisions, provide critical inputs to investment planning and risk assessment, and facilitate multi-stakeholder dialogue on the directionality of change. A prominent example is the International Energy Agency's Global Energy and Climate model, which has been used as a principal tool in the Net-Zero Roadmap to create a benchmark for governments and industries in path to a decarbonized future.[2]

While popular and rising in use, the current trajectories of energy modeling are crucial, but not necessarily sufficient, to meaningfully assess and inform the coupling of net-zero energy and wider sustainability transitions across sectoral and policy domains. For example, existing models rarely account for socioeconomic burdens on communities such as income loss, unemployment, energy security, and energy justice associated with transition away from fossil fuels, nor do they consider potential environmental risks from hard-to-recycle decommissioned materials in the current fossil fuel industries (e.g., platforms, pipelines, and other offshore infrastructure used for extracting oil and gas). These risk the net-zero energy transition misaligned with broader environmental sustainability, justice, and equity for all. As our energy and sustainability options undergo profound change, we must consider the full set of opportunities that models will provide, as well as the challenges that they cannot address, to inform the next generation of frontier science for consolidating sustainability impacts into net-zero energy transitions without lock-in and path dependency to a certain approach.

Energy modeling

Energy models have been widely used to understand the system evolution toward energy security and economic viability, and increasingly in the last decade to inform emissions mitigation strategies toward net-zero futures.[3] They represent system processes, from resource and material extraction, to primary energy production, to energy trade and market, to final energy use in services and industries. To formalize these processes, they include different technical, environmental, and (to some less extent[1]) societal components using various modeling approaches (e.g., optimization, simulation) and data sources, across multiple scales (i.e., from local to national to international), and with different spatial and temporal resolutions.

Details of these models have been systematically reviewed in previous studies for readers interested in deeper understanding.[3] In a nutshell, the current vast landscape of energy modeling features diverse characteristics that can be understood along various dimensions as illustrated in Figure 1. Regardless of where the models stand in this vast landscape, there are important challenges that could impede the effective coupling between net-zero energy and broader sustainability transitions.

Four challenges

There has been a considerable attention to challenges and opportunities of energy system modeling in the past.[5] However, there are important emerging challenges that have not been sufficiently discussed before: those that are related to inherent characteristics of complex coupling between net-zero energy and broader sustainability impacts (Figure 2).

Systemic interactions and trade-off

Net-zero energy transitions involve complex, far-reaching change across society with potentially strong trade-offs and externalities with other sustainability priorities. For example, Brazil, as the world's second largest producer and exporter of ethanol for bioenergy, uses around 8% of its total croplands for sugarcane cultivation, which can increase competition for land with other food crops, as experienced in the significant surge in food

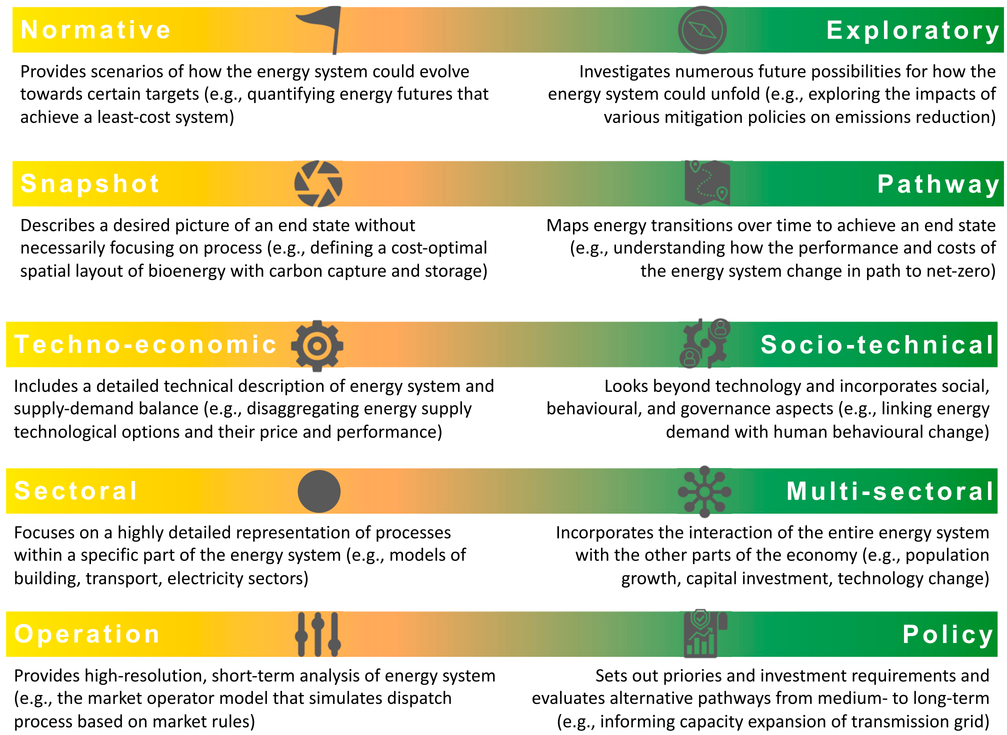

Figure 1. Multiple dimensions that characterize the energy system modeling landscape
The boundaries of models that lay over these dimensions are fluid rather than clear cut, and energy system models can be anywhere between the two sides of the dimensions. For example, the TIMES model is a highly sectoral detailed, techno-economic model with normative projection of least-cost pathways over medium to long-term time horizons for setting out policy priorities.[4]

prices in Brazil in 2015 associated with ethanol production.[6] Meanwhile, decommissioning of fossil fuel assets such as coal-fired plants, with estimated closure liability around $60 billion, to meet Australia's 2050 net-zero emissions target, has created concerns about mounting waste in the environment and reduced options for attaining a circular economy. A sectoral model of energy transitions such as those of bioenergy systems that have no or limited feedback interactions with other parts of the economy (e.g., the impact of large-scale acquisition of land for bioenergy on the welfare of local and Indigenous communities) and the environment (e.g., the impact of biomass for bioenergy on deforestation) may simplify or entirely miss important systemic interactions that drive broader sustainability.

Inconsistency of data and assumptions

The challenge described above requires the integration of multiple analytical models that span the natural and built environment, infrastructures, economic sectors, government and policy jurisdictions, geographical scales, and time frames.[7] By default, these analytical models have been often developed independently from other scientific communities and therefore exhibit significant inconsistencies in their data and assumptions. From a methodological perspective, these inconsistencies impede the effective integration of these models to synthesize holistic analytical insights. For example, in electric power system models, electrified roads and tram lines can be implemented as nodes in a graph theory-based methodological framework whereas in transportation system models they can be treated as edges. Such inconsistencies in the formalization of the two systems need to be reconciled before the models of energy and transportation sectors can be effectively integrated. Even worse, the individual analyses can lead to policy recommendations and interventions that are fundamentally at odds with each other leading to missteps and inaction, such as subsidizing electric vehicle charging stations while neglecting the appropriate location of infrastructure and causing potential traffic congestion.

Heterogeneities across and within society

Global pathways and sectoral strategies for net-zero energy are important for coordination between governments and targeted policy interventions. However, that scale of analysis may not be sufficient to evaluate diverse risks and unintended negative consequences that net-zero pathways might face on the ground among various countries, regions, and local communities. The net-zero transition will be expressed and felt in local communities and places where people live, thus requiring another important (meso-) scale of analysis in modeling. For example, decarbonization in the state of Western Australia has pushed heavy industries (e.g., alumina and oil refineries) that are reliant on fossil fuel-based electricity to phase out. These industries contribute an estimated annual $15 billion and around 18,000 jobs to the state's economy. While some of these fossil fuel industries are seeking to transform and produce

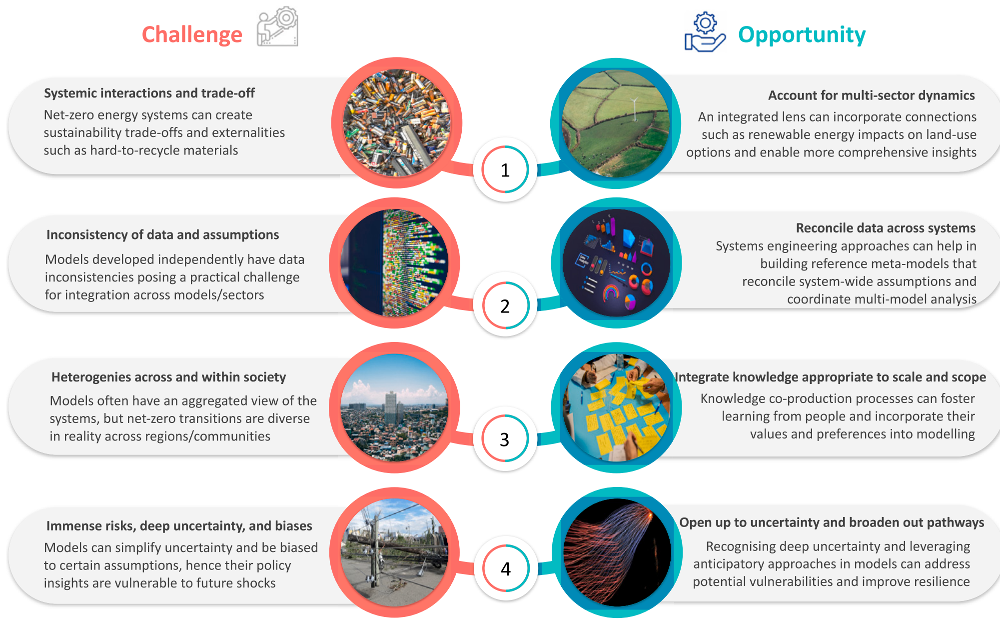

Figure 2. An overview of challenges and opportunities for coupling net-zero energy modeling and sustainability transitions

renewable fuels (e.g., green hydrogen), others decided to entirely cut their operations, raising concerns around energy transition justice for the communities who will face significant loss of local jobs by 2025.

There are also significant gaps in capabilities and investment opportunities that different places face in implementing pathways to net-zero energy while maintaining energy security. For example, sub-Saharan Africa, Latin America, and India are expected to invest approximately 1.5 times more on physical assets as a share of their GDP compared to advanced economies to decarbonize, with a greater share of jobs and local income to be affected.[8] While it is possible for rich countries to abandon fossil fuels in a shorter time frame, for other regions it is a difficult trade-off between energy security, economic growth, and environmental protection. The issue around energy justice and energy security across a heterogeneous society was also an important debate in the recent 2023 United Nations Climate Change Conference (COP28) where the fossil fuel industry's argument was that fossil fuels are needed to ensure a just transition while others outside of their industry were concerned about no roadmap on how to equitably phase out fossil fuels. These indicate the importance of a tailored approach that can incorporate energy justice and security of diverse regions to net-zero transitions and its modeling.

Immense risks, deep uncertainty, and biases

The more inter-connected the energy systems and their modeling are, the more exposed they become to risks and deep uncertainties.[9] An example is the Winter Storm Uri in the United States in February 2021, which led to a huge spike in energy demand and cascading failure in interconnected energy systems due to insufficient planning and preparedness.[10] The resulting disruptions disproportionately affected vulnerable populations, causing at least 111 deaths only in Texas and leaving millions without power, food, and water for several days. The war in Ukraine is another example that gave shocks to global energy systems. Risks and uncertainties, emerging from many dynamic processes across natural, socioeconomic, infrastructure, and governance systems and scales, need to be meaningfully reflected in modeling.[7]

In addition to real-world uncertainties, the modeling process also involves a series of biased choices regarding methods, input data, and their interrelationships.[11] By assigning more weight to certain factors due to different values and diverse solutions among the various stakeholders involved, intentionally or not, the modeling results can make one outcome appear more favorable, probable, or significant than others. For example, the projections of solar photovoltaic generation can vary by a factor of two across various scenarios by different models.[12] This can be associated with choices and assumptions of their modeling, often biased to optimistic or pessimistic expectations.[12] Expecting "the" answer to our policy questions based on limited scenarios of each model creates an overly narrow evaluation of uncertainty and leads erroneously to one-track/limited pathway options for attaining a net-zero and sustainable future.

Four opportunities

The combination of challenges identified necessitates progress to better couple net-zero energy with broader sustainability transitions through modeling. We used our collective experience from a range of approaches that were implemented and/or extensively researched in Australia to highlight four opportunities that are also applicable globally across contexts and locations (Figure 2).

Account for multi-sector dynamics

Navigating transitions to net-zero energy while balancing other sustainability priorities requires an integrated understanding across technological, social, and behavioral options that reduce emissions from both supply- and demand-side and an evaluation of outcomes across a broad range of socioeconomic and environmental aspects. Modeling in these use-cases needs to account for systemic interlinkages such as the impacts on land-use options, the competitiveness from scaling of bioenergy production, and the implications for carbon sequestration, food supply, and other industrial inputs. To demonstrate this model desiderata, we use an example from Australia's investment in the next generation of net-zero pathway modeling.[13] A dynamic multi-national general equilibrium model, with detail of negative emission and decarbonization technologies in power generation, transport, iron and steel manufacturing, crop, and livestock sectors, places a central role in the modeling system to explore how international climate actions influence Australia through globalization and trade.[13] The model then connects with an Australian sub-national dynamic general equilibrium model and partial equilibrium models of energy, transport, agriculture, land-use, climate, water, biodiversity, and material flows, as well as nutrition information. This modeling, used in the Australian National Outlook, allows us navigate complex challenges involved in achieving sustainable prosperity in energy and other sectors. It informed pathways where sustainability and economic growth can be partners rather than competitors,[13] a multi-sector approach from which we can learn and transfer to other applications.

Reconcile data across systems

The presence of multiple analytical models to account for multi-sector dynamics necessitates state-of-the-art system integration. Model-based systems engineering has been used extensively to develop complex human-natural systems that span disciplinary boundaries, coordinate disparate scientific teams, and engage with multiple stakeholders and their requirements. To do so, it creates a graphically depicted, reference meta-data model that gathers, organizes, and ultimately reconciles data and assumptions across systems. From this reference model, multiple analyses can be carried out in a coordinated fashion. In another example from Australia, the SysML, a systems engineering modeling language, is used to develop a multi-energy system reference architecture that includes coal, oil, natural gas, electric power, hydrogen, potable water, and wastewater management system. Using graph theory, such a reference architecture, can be translated into a hetero-functional graph for resilience analysis or transformed into an optimization model that enables real-time state estimation of operations or long-term net-zero pathway planning.

Integrate knowledge appropriate to scale and scope

Transitions to net-zero encompass multiple levels and scales of governance. This complexity within and across society requires combinations of top-down (i.e., global to national) and bottom-up (i.e., local to regional) approaches to define, monitor, evaluate, and learn from a diversity of priorities, decision-making processes, and investment opportunities. To do so, net-zero energy modeling can be supported by co-creation processes that variously engage stakeholders to draw in and benefit from diverse knowledge.[14] For example, cognitive mapping as a problem structuring approach can be useful for understanding the perceptions of diverse stakeholders in a region about priorities in net-zero energy transitions and capture multiple facets of complex energy system problems around controversial issues such as unintended consequences of decarbonization process for local energy security and justice.[15] Co-production processes can also help in building a shared understanding about solutions to a common problem while also creating legitimacy for processes and options. For example, serious games, as a tool for imagining alternative realities and facilitating discussions, can be useful in energy modeling by offering stakeholders an interactive platform to see in real time the impact of various energy system configuration on cost, supply, and emissions. These interactive platforms underpinned by models have been used at various scales to examine portfolios of mitigation options for net-zero futures (e.g., En-ROADS[16]).

Open up to uncertainty and broaden out pathways

Enhancing responses to future risks requires building capacity to open up to deep uncertainties and anticipate systemic vulnerabilities, such as disruption in infrastructures or a surge in demand. These capacities bring new opportunities for creating value, reveal leverage points within the system for building resilience, and widen the set of stakeholders with shared responsibilities for investing in solutions. For example, the energy transition coinciding with disaster recovery—both of which are playing out in many regions globally—provides opportunities to develop modeling tools that support resilience-building and net-zero energy transitions with equitable benefits across community. The Bega Valley region in Australia is one of these communities severely impacted by Black Summer bushfires in 2019–2020. In their recovery efforts, they invested in several projects, one of which was a 5MW renewable microgrid array facility, to improve reliability and incorporate climate disaster risk. The project drew on anticipatory assessment and pathways approaches to explore cascading risks, opportunities, values, costs, and benefits associated with different structures of regional renewable micro-energy grids under different possible futures.[17] The framing was developed in this way to support subsequent modeling that provides credible evidence-based assessments of the resilience and sustainability outcomes of different models to regional energy transitions.

Turning science into action

The net-zero transitions and their related challenges and opportunities are too diverse and heterogeneous to be encompassed primarily by any single fit-for-purpose approach in practice. A suite of approaches—qualitative and quantitative and embedded in inclusive engagement processes—is needed in development and testing of models with the selection predicated on the context of application. The use of these models needs to be suitably embedded within the appropriate process of decision making and power dynamics that influence why and how they are applied.[18] Such a flexible and adaptive approach to modeling can guide the future of science in integrating sustainability impacts into net-zero energy changes without being dependent on a specific method.

ACKNOWLEDGMENTS

Icons in Figure 1 are by tulpahn, SBTS, Adrien Coquet, Aficons, Besokpagi, Alice Design, Gregor Cresnar, Siti Nurhayati, and Ahmad from the Noun Project under a Creative Commons License CC BY 3.0. Images in Figure 2 are by John Cameron,

Markus Spiske, Choong Deng Xiang, Annie Spratt, Carl Kho, Hunter Harritt, Charles Deluvio, and FORTYTWO from Unsplash.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Trutnevyte, E., Hirt, L.F., Bauer, N., Cherp, A., Hawkes, A., Edelenbosch, O.Y., Pedde, S., and van Vuuren, D.P. (2019). Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. One Earth *1*, 423–433. https://doi.org/10.1016/j.oneear.2019.12.002.
2. IEA (2023). Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach (IEA). https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.
3. Fodstad, M., Crespo del Granado, P., Hellemo, L., Knudsen, B.R., Pisciella, P., Silvast, A., Bordin, C., Schmidt, S., and Straus, J. (2022). Next frontiers in energy system modelling: A review on challenges and the state of the art. Renew. Sustain. Energy Rev. *160*, 112246. https://doi.org/10.1016/j.rser.2022.112246.
4. Loulou, R., and Labriet, M. (2008). ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. Comput. Manag. Sci. *5*, 7–40. https://doi.org/10.1007/s10287-007-0046-z.
5. Pfenninger, S., Hawkes, A., and Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. Renew. Sustain. Energy Rev. *33*, 74–86. https://doi.org/10.1016/j.rser.2014.02.003.
6. Maitah, M., Procházka, P., Smutka, L., Maitah, K., and Honig, V. (2019). Analysis of the Impact of Ethanol Production on Agricultural Product Prices in Brazil. Sugar Tech *21*, 773–779. https://doi.org/10.1007/s12355-019-00709-w.
7. Reed, P.M., Hadjimichael, A., Moss, R.H., Brelsford, C., Burleyson, C.D., Cohen, S., Dyreson, A., Gold, D.F., Gupta, R.S., Keller, K., et al. (2022). Multisector Dynamics: Advancing the Science of Complex Adaptive Human-Earth Systems. Earth's Future *10*, e2021EF002621. https://doi.org/10.1029/2021EF002621.
8. Krishnan, M., Samandari, H., Woetzel, J., Smit, S., Woetzel, J., Smit, S., Pacthod, D., Pinner, D., Nauclér, T., Tai, H., et al. (2022). The Net-Zero Transition: What it Would Cost, what it Could Bring (McKinsey & Company). https://www.mckinsey.com/capabilities/sustainability/our-insights/the-net-zero-transition-what-it-would-cost-what-it-could-bring.
9. Srikrishnan, V., Lafferty, D.C., Wong, T.E., Lamontagne, J.R., Quinn, J.D., Sharma, S., Molla, N.J., Herman, J.D., Sriver, R.L., Morris, J.F., and Lee, B.S. (2022). Uncertainty Analysis in Multi-Sector Systems: Considerations for Risk Analysis, Projection, and Planning for Complex Systems. Earth's Future *10*, e2021EF002644. https://doi.org/10.1029/2021EF002644.
10. Doss-Gollin, J., Farnham, D.J., Lall, U., and Modi, V. (2021). How unprecedented was the February 2021 Texas cold snap? Environ. Res. Lett. *16*, 064056. https://doi.org/10.1088/1748-9326/ac0278.
11. Moallemi, E.A., Zare, F., Reed, P.M., Elsawah, S., Ryan, M.J., and Bryan, B.A. (2020). Structuring and evaluating decision support processes to enhance the robustness of complex human–natural systems. Environ. Model. Softw. *123*, 1045–1051. https://doi.org/10.1016/j.envsoft.2019.104551.
12. Jaxa-Rozen, M., and Trutnevyte, E. (2021). Sources of uncertainty in long-term global scenarios of solar photovoltaic technology. Nat. Clim. Chang. *11*, 266–273. https://doi.org/10.1038/s41558-021-00998-8.
13. Hatfield-Dodds, S., Schandl, H., Adams, P.D., Baynes, T.M., Brinsmead, T.S., Bryan, B.A., Chiew, F.H.S., Graham, P.W., Grundy, M., Harwood, T., et al. (2015). Australia is 'free to choose' economic growth and falling environmental pressures. Nature *527*, 49–53. https://doi.org/10.1038/nature16065.
14. Moallemi, E.A., Zare, F., Hebinck, A., Szetey, K., Molina-Perez, E., Zyngier, R.L., Hadjikakou, M., Kwakkel, J., Haasnoot, M., Miller, K.K., et al. (2023). Knowledge co-production for decision-making in human-natural systems under uncertainty. Glob. Environ. Change *82*, 102727. https://doi.org/10.1016/j.gloenvcha.2023.102727.
15. Moallemi, E.A., and Malekpour, S. (2018). A participatory exploratory modelling approach for long-term planning in energy transitions. Energy Res. Soc. Sci. *35*, 205–216. https://doi.org/10.1016/j.erss.2017.10.022.
16. Holz, C., Siegel, L.S., Johnston, E., Jones, A.P., and Sterman, J. (2018). Ratcheting ambition to limit warming to 1.5 °C–trade-offs between emission reductions and carbon dioxide removal. Environ. Res. Lett. *13*, 064028. https://doi.org/10.1088/1748-9326/aac0c1.
17. O'Connell, D., Helfgott, A., Flett, D., Wise, R., Meharg, S., Marinopoulos, J., Lee, A., Gorddard, R., Mesic, N., Tieman, G., and Chan, J. (2021). Towards Visions, Options and Pathways for an Adaptive Future in Bega Valley: Building National Capability for Enabling Resilience Investment (CSIRO). https://doi.org/10.25919/3wd4-wh31.
18. Stirling, A. (2014). Transforming power: Social science and the politics of energy choices. Energy Res. Soc. Sci. *1*, 83–95. https://doi.org/10.1016/j.erss.2014.02.001.