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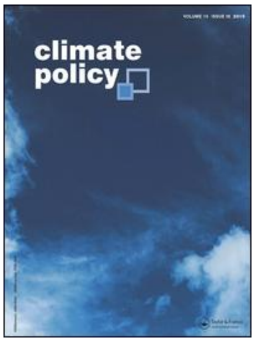

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OUTLOOK ARTICLE

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Modelling net-zero emissions energy systems requires a change in approach

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ABSTRACT

Energy modelling can assist national decision makers in determining strategies that achieve net-zero greenhouse gas (GHG) emissions. However, three key challenges for the modelling community are emerging under this radical climate target that needs to be recognized and addressed. A first challenge is the need to represent new mitigation options not currently represented in many energy models. We emphasize here the under representation of end-use sector demand-side options due to the traditional supply side focus of many energy models, along with issues surrounding robustness in deploying carbon dioxide removal (CDR) options. A second challenge concerns the types of models used. We highlight doubts about whether current models provide sufficient relevant insights on system feasibility, actor behaviour, and policy effectiveness. A third challenge concerns how models are applied for policy analyses. Priorities include the need for expanding scenario thinking to incorporate a wider range of uncertainty factors, providing insights on target setting, alignment with broader policy objectives, and improving engagement and transparency of approaches. There is a significant risk that without reconsidering energy modelling approaches, the role that the modelling community can play in providing effective decision support may be reduced. Such support is critical, as countries seek to develop new Nationally Determined Contributions and longer-term strategies over the next few years.

Key policy insights

- Energy systems that reach net-zero greenhouse gas emissions will be radically different to those of today, necessitating a modelling analysis re-think.
- On modelled options for mitigation, a range of demand-side measures are often absent resulting in a risk of over-reliance on carbon dioxide removal (CDR) and leading to concerns over robustness of corresponding pathways.
- Regarding models for policy, there is significant scope for improvements, including the use of scenarios that help imagine the radical change that will be required, techniques for improving the robustness of emerging strategies, and better alignment with broader policy goals.

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Energy models; net-zero emissions; low carbon transitions; decision support

1. Introduction

Since the 1970s, energy models have represented stylized versions of energy systems (Gilliland, 1975; Slesser, 1975). They can be applied in an explorative way, using, for example, scenario or gaming approaches to

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explore the system's possible evolution in future years. They can also be used to explore the different parts of the system in a single framework, and to understand how the system functions at a detailed level at any specified time (Bankes, 1993). They formalize the component parts of the system and their interactions, and allow for structured thinking about the implications of significant system reconfiguration. Energy modelling analysis has been embedded into national energy strategy deliberation, notably when exploring system decarbonization (Waisman et al., 2019), and has helped inform the climate and energy strategy discourse in the past decade in countries as diverse as the UK (Trutnevyte et al., 2016), South Africa (Altieri et al., 2016) and Canada (Sawyer & Bataille, 2016).

The 2015 Paris Agreement, and the publication of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (Masson-Delmotte et al., 2018), highlight the need for stronger mitigation action than previously envisaged, with CO_2 emissions needing to be reduced to net-zero around 2050 to limit temperature rise to 1.5°C. In parallel, non-CO_2 emissions require reductions commensurate to those assessed under 2°C targets. In response, a number of countries have legislated for net-zero GHG targets, including the UK and Sweden (CCC, 2019). Many more are exploring the implications of how such targets can be achieved. Reaching them implies that energy systems be close to net-zero emissions, or even net-negative, and energy modellers need to consider how to respond to support this agenda. Increased ambition brings new challenges that national modelling teams are only now starting to grapple with (Glynn et al., 2019; Oshiro et al., 2018; Pye et al., 2017). These include the removal of emissions 'headroom' (or residual emissions) by the net-zero target year, more rapid mitigation rates, consideration of new fuel-technology pathways, and determining approaches to climate policy framing, including equity considerations. Another critical challenge is determining how well energy models account for deep uncertainties, societal preferences and political realities under net-zero – while recognzsing that models are not the only input to decision-making, and that there is a limit to the extent to which they can account for these factors.

The issues discussed in this paper were in large part informed by an expert workshop held on the challenges of net-zero emission targets for energy systems modelling, particularly in the context of supporting government energy and climate policy. The workshop, jointly hosted by the UK Energy Research Centre (UKERC) and University College London (UCL), was titled *Hitting net-zero: the role of energy modelling in national pathway analyses* and was held in London, in January 2020. Workshop attendees included model practitioners and consumers of model results from a range of academic, government, advisory and consulting organizations. Among energy systems models, the focus was on those that provide a whole system perspective (Pye & Bataille, 2016), covering all energy-using sectors (i.e. industry, buildings, transport), and energy-supply sectors (i.e. upstream fossil fuel resources, electricity generation, and other fuel production e.g. hydrogen and biofuels).

The issues raised at the workshop fell into the categories of (1) scope, (2) function and (3) practice. *Scope* (1) concerns how models can be extended to represent a wider set of mitigation options, given the increased stringency of a net-zero target. *Function* (2) refers to the capability of models to adequately represent net-zero energy systems. This will be determined by model structure (paradigm, underlying equations) and linkages to other models better placed to represent aspects of the system. P*ractice* (3) addresses the appropriate use of models for undertaking net-zero analysis. This includes consideration of uncertainty, scenario design, and enhanced engagement and collaboration with peers and stakeholders from multiple disciplines throughout the modelling process. Crucially, all three issues are interlinked; for example, extending modelling scope to better capture demand-side shifts in energy-using practices may require enhanced links to other models or improved representation of these dynamics within the model (function) and a stronger interdisciplinary approach to include broader expertise on socio-technical transitions (practice). Required changes to model function may arise from extending the scope, or from a recognition that net-zero targets will mean existing options need better representation e.g. storage in a higher renewable electricity system.

The paper is structured as follows. In section 2, we first characterize a net-zero emissions energy system, highlighting the differences with those that are only partially decarbonized. Reflecting the outcome of the workshop, we then outline the implications of a net-zero energy system on current modelling *scope*, *function* and *practice* (sections 3–5). In section 6, we close by highlighting the key elements that any future research agenda should include to improve the analytical support that the modelling community can provide to national decision makers. This is time-critical for the United Nations Framework Convention on Climate Change (UNFCCC) country-led system of Nationally Determined Contributions (NDCs) set in motion under the Paris Agreement (United Nations, 2015). It will support country efforts to propose low emission development strategies that strengthen NDC pledges, and inform longer-term targets, including net-zero emissions ambition.

2. Characteristics of a national net-zero CO_2e emissions energy system

Net-zero emissions targets adopted by national governments have to date focused on decarbonizing the whole economy, covering energy supply and demand, as well as other sources of emissions including industrial processes, agriculture, and land use and forestry. Given that the energy system is the dominant source of emissions in most countries, that many decarbonization options exist for this source, and that emissions from other sectors such as agriculture will be extremely challenging to reduce to zero, this paper takes forward the argument that net-zero or net-negative emission energy systems will be required.

An economy that does not produce greenhouse gas (GHG) emissions from the use of energy will be radically different to that observed today. The implications are wide ranging, from changing working practices, re-thinking urban planning and infrastructure, shifting transport choices away from privately owned fossil fuel powered cars, using different types of heating technologies, moving to higher capital intensity but lower operating cost systems, through to changing how goods are produced and consumed. Imagining such a radical transformation is a first step to being able to determine its implication for energy modelling.

There are multiple ways of defining net-zero emissions energy systems (Rogelj et al., 2015). Here we consider them to be systems where net total annual emissions of CO_2e are zero or negative, including removals. This definition covers only territorial emissions, the basis for national targets, and does not account for embodied emissions in imports. As we have argued, an energy system that meets this definition will be radically different to one that is only partially decarbonized. A key feature is the restricted 'headroom' for residual emissions that allows for net positive GHG emissions. This results in less flexibility to balance action between energy system sectors in terms of comparative mitigation, as all need to either be fully decarbonized, or have their residual emissions offset by land use or technological carbon dioxide removals (CDR), the latter through biomass use or direct air capture of CO_2, both followed by carbon capture and storage (CCS) (Hepburn et al., 2019). The timing of action also changes, moving from consecutive, incremental change (e.g. tackling easier sectors first and leaving harder to mitigate sectors until later) to concurrent actions that result in large structural changes, as all sectors move to decarbonize rapidly.

A net-zero energy system will therefore require new technological solutions focused on hard-to-decarbonize sectors responsible for residual emissions (Davis et al., 2018). Examples include new pathways for synthetic fuels (e.g. synthetic kerosene for aviation), and emerging low carbon industrial processes in iron and steel, and cement production (Bataille, 2019). At the same time, options that were considered feasible under an 80% or 90% reduction target may now be redundant e.g. fossil fuel-based CCS solutions that do not provide near 100% capture and/or that result in upstream emissions.

Where residual emissions persist in the absence of supply side solutions, critical elements of achieving a net-zero energy system could include CDR, changes to how energy is used to provide energy services and the level of demand for those services (demand-side options). While CDR, notably bioenergy with carbon capture and storage (BECCS), is seen as a key option, the potential scale and rate of deployment, as well as issues concerning feasibility and sustainability, have given rise to serious questions about its role (Anderson & Peters, 2016; Fuss et al., 2014). Demand-side options could also play a role in reducing energy demand and thereby lowering residual emissions that need to be balanced by removals (Grubler et al., 2018; van Vuuren et al., 2018). Alongside efficiency gains and shifts towards alternative means of energy service provision, options include reducing energy service requirements, expanding smart energy storage systems, reduced use of materials or material substitution in industry, lower mobility levels due to changes in work or leisure practices, and improved energy use in buildings due to construction practices.

A net-zero energy transition will require the adoption of a broader set of measures over relatively short timescales of around 30 years, impacting on all sectors and multiple actors, with significant implications for the necessary policy packages. Given the disruptive nature of this transition, understanding the responses required from different types of actors in society to effect the necessary change will be critical. A central question that emerges is whether the range of energy models in use for this type of analysis (Pye & Bataille, 2016) can adequately represent the transition from today's fossil fuel-dominated energy system to one that is emissions-neutral.

3. Issue 1: expanding the mitigation option space

The stringency of a net-zero target means new or more ambitious options will be required across all sectors or, at a minimum, should be considered.

A first key issue is the deficit in representing demand-side options, as set out in Hardt et al. (2019). The 'avoid-shift-improve' framework highlighted in Creutzig et al. (2018) can help to consider the full range of demand-side measures, including avoiding demand for energy use, shifting to more efficient energy demand provision, and reducing energy use through improvements to the efficiency of technologies and buildings. Most models construct an energy system based on exogenous energy service demand projections. While energy efficiency is often represented to an extent, solutions that lead to avoiding energy service demand, or that shift to cleaner forms of demand provision, are often missing. This includes using less materials in industrial production through material efficiency, circular economies, and reduced consumption of goods (IEA, 2019), changing demand for mobility and/or using more efficient transport modes (Brand et al., 2018), lowering building energy demand through retrofitting to improve energy efficiency (Rosenow et al., 2018), and reducing the demand for energy services such as mobility by teleworking (Hook et al., 2020).

A key impact of these measures is that they reduce the overall size of the energy system and thus lower supply side investment requirements (Napp et al., 2019). Not unimportantly, this leaves more primary factors of production (capital and labour) available for broader economic growth and welfare, which could lead to emissions rebound if emissions are not constrained (Bataille & Melton, 2017). Current modelling approaches, however, may still fail to capture and reflect demand-side dynamics because of their typical supply side focus. These dynamics include social barriers to expanding many novel options e.g. resistance to transport infrastructure changes, or the dynamic nature of the drivers of demand, which will change at different rates over time according to economic growth and decline, and changing lifestyle trends. Challenges to including these measures include a limited evidence base, the need for interdisciplinary input, and representing associated rebound and spillover effects (Sorrell et al., 2020).

A second key issue concerns CDR options. At a global level, the push towards finding new model solutions has increasingly brought CDR options to the fore, allowing for compensatory CDR (CO_2 emissions that are allowed now and drawn down later) and for offsetting emissions from hard-to-mitigate sectors. The cost-effectiveness of these diverse solutions in climate-constrained systems increases with high carbon prices, often resulting in models choosing strong CDR deployment, as evidenced in integrated assessment model[1] (IAM) scenarios. Many national-scale models have yet to integrate the range of CDR options (DDPP, 2015), in part due to lower levels of climate policy ambition in the past. There are two concerns with modelling CDR. Firstly, the questionable robustness of strategies that rely on untested large-scale CDR deployment to decarbonize the energy system or provide negative emissions to the rest of the economy (Gough et al., 2018; Obersteiner et al., 2018). Secondly, the potential CDR effect of delaying action, which underplays the urgent need to deploy a diverse set of options today across multiple sectors (Köberle, 2019), and gives rise to questions of intergenerational equity (Shue, 2017). Crucially, it should be recognized that such options are often not part of the policy discussion (Peters & Geden, 2017), and therefore may be some years away from deployment. A more explicit and active consideration of the role for CDR in scenario design will be important (Rogelj et al., 2019) and should replace the current approaches that leave deployment of CDR to the model solution.

The third key area relates to new fuel-technology pathways that may require enhanced representation of specific end use sectors. A major focus needs to be on hard-to-mitigate sectors, including international transport and industry, which are often modelled at an aggregated level. Options to decarbonize energy-intensive sectors also need to be included, such as lower clinker ratio cements, the use of lower GHG hydrogen for fertilizer and general chemicals production, and zero carbon steel production through the use of hydrogen in the direct reduction process combined with the electric arc furnace process (Bataille, 2019). New fuel pathways should also be represented, including the 'circular carbon economy', where hydrogen production and captured CO2 are used to produce synthetic fuels for the transport sector via processes including Fischer Tropsch, methanation and methanol synthesis (Energy Transitions Commission, 2018). Where synthetic fuels are included in models, their high costs and thermodynamic efficiency also need to be considered.

4. Issue 2: enhancing model functionality

Incorporating new options and representing new system configurations in existing models necessarily raises the question of the adequacy of the modelling framework. Simply put, even if the scope is expanded, does the model framework have the technical capability required to adequately represent a net-zero energy system? Responding to this question requires taking a critical look at model structure and typology, and at links between model frameworks. Key issues include the need for deeper model linkages that enhance sectoral and wider economy representation, improved spatio-temporal representation of the system (e.g. for electricity systems), a stronger focus on modelling 'real world dynamics' to better support effective policy implementation, and more systematic consideration of model boundary issues.

Many energy models apply a 'whole system' approach, playing to strengths that include the representation of system interconnectedness (e.g. electricity demand and supply), sectoral trade-offs (e.g. allocation of limited resources, contribution to mitigation), and internal consistency (timing, depth, and resource use of mitigation actions). Such models, however, often lack detail, particularly across emission sources or system solutions that come into much sharper focus for a net-zero system.

A strength of whole system representation is the ability to explore sector trade-offs, but this may arguably become less important when modelling net-zero, given that most parts of the economy need to move to net-zero emissions. A shift to modular-based models that represent national energy systems and include enhanced sectoral detail may be able to utilize the strengths of both. A good example is the energy modelling system used to inform energy and climate policy in Ireland, which combines a whole system approach with sectoral modelling for power systems, buildings and transport (Deane et al., 2012; Mulholland et al., 2017).

Linkages to macroeconomic models are also important in view of the broader economic impacts, trade-offs, or more structural changes to economic paradigms potentially implied by reaching net-zero. While commonly used (Glynn et al., 2015; Pye & Bataille, 2016), approaches to macroeconomic modelling have been relatively simplistic. Improvements are needed to better understand the dynamics between energy efficiency gains, energy and emissions rebound effects and economic growth (Sakai et al., 2019), and absolute decoupling of economic growth and emissions (Haberl et al., 2020), which is often assumed to be achievable in current energy models.

The aggregation required for whole system energy models has often led to criticism about the limited spatio-temporal resolution of such models (Pfenninger et al., 2014). This is particularly important for high electrification systems that have significant renewable-based generation and may require flexibility options e.g. storage or demand-side response. Net-zero systems are likely to rely more heavily still on electrification as low-but-not-zero carbon options become less deployable. Modelling advances that improve representation of highly electrified systems include linking frameworks to assess flexibility and storage requirements (Welsch et al., 2014), or parameterizing models (without structural change) to reflect system requirements (Collins et al., 2017).

A further criticism concerns the limited representation of real-world implementation in models, and the resulting difficulty in assessing the effectiveness of policy options needed to bring about change. The long-term cost-effectiveness of energy pathways, a traditional topic for model-based decision support, may no longer be the key question. Considering the long lead times for some measures, an understanding of what deliverable near-term actions can be undertaken and implemented that align to long-term ambitions may become a higher priority. Models that better represent policy effectiveness, the distribution of impacts, the risk of low policy realization rates, innovation, and broader responses to meeting net-zero targets by key actors (householders, businesses, the finance sector, government) may be more suited to this objective. These may notably include socio-technical orientated approaches (Geels et al., 2016; Holtz et al., 2015; Li & Strachan, 2017) and agent-based modelling (Barazza & Strachan, 2020; Farmer et al., 2015).

Finally, energy system boundary issues are likely to come into sharper focus. This includes interconnectedness of national energy systems, linkages with non-energy systems, and issues of emission responsibility.

Stronger integration of national energy systems could reduce future costs of low carbon infrastructure, and increase system flexibility through grid interconnection (Zakeri et al., 2018). In most national contexts, the current and future impacts of climate change call for a deeper understanding of the importance of wider ecosystem services. This implies that energy system models should increasingly account for non-energy sectors, particularly where there are significant interdependencies between environmental systems. Nexus modelling – accounting for water and land use in energy and climate analyses – is an established approach that can help to provide such insights (Howells et al., 2013), but more research in this area is needed to cast the net still wider. On emissions responsibility, if countries are to consider their overall contribution to global warming, questions of consumption-based emissions (Afionis et al., 2017; Tukker et al., 2020), the ethics of international offsetting, imports of specific commodities e.g. bioenergy, or the key question of land use systems, become harder to ignore.

5. Issue 3. changing modelling practice

Modelling a net-zero future raises concerns about how energy modelling is carried out. This section presents four proposed changes to current practice: (i) a broader re-imagining of the future energy system and consideration of a wider range of uncertainties, (ii) more reflection on the choice of targets and their implementation, (iii) ensuring alignment with wider policy objectives, and (iv) increased research community engagement and collaboration.

Firstly, modelling should help build scenarios that include radically different future economic systems (McCollum et al., 2020). This not only includes exploring the rapid techno-economic changes required to achieve net-zero targets, but also capturing the potential implications of related disruptive events or socio-political changes that might emerge. Examples include the current COVID-19 crisis that may have lasting effects on patterns of mobility and work, and on sectors of the economy; disruptive changes that might occur from climate impacts; or radical policy interventions driven by a recognition that climate change requires an emergency response. Such scenarios may be deemed unlikely or outside of what is politically feasible today; nevertheless, such practice makes sense given the profound transformation that achieving net-zero requires. Discussions around the dynamics of political feasibility (Jewell & Cherp, 2020), which are also critical, can then follow.

For modellers, a key challenge will be representing such types of dramatic change. Whether modelled endogenously or soft linked to other analyses, a broadening of the disciplinary reach will be needed to help imagine them. This might include working with researchers in other fields who are exploring different futures e.g. digitalization, automation or other changes to work practices (RSA, 2019). This also means a stronger focus on uncertainty analysis. While progress has been made in using formal uncertainty analysis techniques (Yue et al., 2018), the energy modelling community has much experience to draw on from other groups. Noteworthy literature will include decision making under deep uncertainty, which pioneered techniques that explore robust decision making (Guivarch et al., 2017), and post-normal science thinking (Petersen et al., 2011; Van Der Sluijs et al., 2005). Such approaches give insights into how decision makers can handle large-scale uncertainty, and where model solutions are most sensitive to different types of uncertainty.

Secondly, models are well positioned to explore a range of climate targets (reflecting national allocation criteria), and the impacts of how and when they are achieved. Whilst national targets are political choices, models can be used to highlight the impact of alternative allocation approaches (e.g. that account for equity) for possible global carbon emission budgets (Robiou Du Pont et al., 2017; van den Berg et al., 2019), and implications for domestic action of achieving net-zero emissions at different points in time. How targets are implemented also matters, and again models can provide insights on the implications of setting cumulative carbon budgets versus a single net-zero target year at a point in time. Pye et al. (2017) considered both options for the UK, and showed how equity considerations and a cumulative budget approach necessitated much stronger action than under existing government climate policy. The main point is that policy ambition and implementation are not settled by the use of a net-zero target; the debate around level of ambition and pace of implementation is still very much live as highlighted by (Anderson et al., 2020).

Thirdly, there is the issue of aligning net-zero studies with other domestic priorities. Modellers need to ensure that modelling for policy support does not focus solely on an emissions goal, but rather studies net zero as part of a shift towards a more sustainable economy that can reduce inequality and support the UN Sustainable Development Goals (SDGs). Insights on combining these objectives and understanding their co-benefits will increasingly be at the forefront of national discussions. Waisman et al. (2019) highlight the importance of this issue. Examples include: accounting for broader environmental quality goals in China and India, where reductions in air pollution have aligned with decarbonization; exploring strategies for reducing income inequality and unemployment in South Africa whilst decarbonizing the economy; and considering the benefits of sustainable land and forestry management as part of a broader emissions reduction strategy in Brazil.

Finally, there remain issues of engagement to address the accessibility, transparency and communication of models, including their input assumptions and their outputs. Learning can be derived from both UK and international experience (van Sluisveld et al., 2017). A push towards new solution spaces – beyond traditional engineering thinking towards socio-political issues – requires a more interdisciplinary approach (Li & Pye, 2018). This includes engaging with government and other stakeholders at multiple and early points of any future policy cycle. Modelling should also be able to test the socio-political feasibility of different decarbonization pathways under particular economic and political systems (Geels et al., 2016). Increased engagement requires the modelling community to see itself as part of a broader research community, where collaboration is viewed as essential to tap the range of disciplinary expertise. Involving a broader peer community means opening up for scrutiny and critique, both in terms of open documentation and open access / sourcing of models, clarity in presentation of results, and also through participatory approaches, such as through structured workshop approaches (Bistline et al., 2020; Pye et al., 2018). Creating transparency in modelling assumptions should also support deeper and more systematic critique.

6. Conclusions: shaping the future modelling research agenda for net-zero

The net-zero agenda changes the modelling game, with a key set of challenges that need to be faced in order to provide more effective analyses for decision makers. While it is evident that some challenges are not new, there is an urgency to ensure they are met as soon as possible, given the role that modelling needs to play to help inform national energy and climate policy right now. On scope, this includes the need for radicalism in exploring solutions, including those not yet deemed politically palatable or salient, but also careful consideration of options such as CDR that might impact robustness of future strategies. On function, this requires revisiting modelling tools to judge their applicability to net-zero analyses. This includes a reoriented focus towards how measures can be effectively implemented as opposed to merely what measures can be used. There is also a need to ensure that the models can represent the new system configurations that will emerge. Finally, on practice, this will require meaningful participation in the process by multiple experts and stakeholders, and collaboration that recognizes the variety of disciplinary strengths needed from different research teams. Modellers also needs to be open to radical scenario thinking, including a robust recognition of uncertainty, and be cognizant of the many priorities that decision makers are balancing. The energy modelling community has the opportunity to present a much wider set of evidence to inform net-zero policy making as time-critical decisions are made about decarbonizing energy systems; however, changes in modelling scope, function, and practice are required.

Note

1. A type of model that attempts to represent the relationships between society, economy, biosphere and atmosphere within a single analysis framework.

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