Increasing the reliability of energy system scenarios with integrated modelling: a review

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Abstract

Systems models are an important tool for policy and energy planning decisions. These models generally fall into one of three modelling paradigms: energy economy, capacity expansion or power sector planning. Recent work seeks to combine these paradigms into an integrated framework to leverage the benefits of different model types. There is also interest and research in representing more system interactions to expand the modelling nexus. However, this increases model complexity and risks creating more black box models that are not well understood or trusted by users or policymakers. To understand the trade-offs and best practices of using combined models, we review current modelling practices, including an overview of the different modelling paradigms in the literature, how combined modelling has been applied to date and how the nexus has been represented in different modelling applications. Building on the literature review, we held a series of expert elicitation workshops to gain insight from energy modelling domain experts who use combined models. Finally, we encapsulate these findings and best practices into a modelling evaluation framework. We find that while there is interest and research being done in these areas, there are no set standards for how to build these types of models, resulting in a wide range of practices. Increasing model complexity to develop fully hard-linked coupled models that are also trustworthy and transparent generally requires more time and resources than is worthwhile. Instead, the focus should be on avoiding black box models by having a clear modelling purpose and developing best practices that allow for clarity and transparency. Expanding the nexus to include attributes such as biodiversity and cultural security presents a challenge and representing them as a cost is not congruent to equitable policy. These aspects could be better incorporated into analysis using stakeholder debate and citizens’ assemblies.

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1. Introduction

Transitioning the primary energy supply to utilize non-emitting generation technologies requires a holistic assessment of impacts, mitigation and adaptation policies to ensure that actions in one area do not cause unintended consequences in another area [1, 2]. For example, dedicating land to biofuel production could impact food availability, while planning for new hydroelectric facilities must consider plans for irrigation. Should these interactions be ignored, there is the risk that natural, human and financial resources are wasted.

Systems modelling is one of the main tools used by policy makers to inform decisions on such multicriteria challenges. In general, there are two main model categories used for different types of decision-making [3]. The power engineering community has focussed on engineering solutions that replace the primary energy supply (largely fossil fuels) with a system fuelled predominantly by intermittent renewables and non-emitting power generation technologies. The energy-economy modelling communities have focussed on building models that capture the interaction of individual behaviour with climate policy (carbon pricing, flexible fuel standards, carbon trading) to be assessed within the framework of a national or jurisdictions economy. These disconnected responses create decision-making inertia which is problematic given the increasingly short timescale [4] in which meaningful climate mitigation strategies need to be invoked.

Furthermore, the energy-economy policy modelling community is only just beginning to consider assessment of the interdependency of energy security with food and water security. The establishment of the United Nations Sustainable Development Goals (SDGs) [5] and the United Nations Declaration of the Rights of Indigenous Peoples (UNDRIP) [6] illuminates two additional dimensions of natural security (eco-system health and biodiversity) and cultural security that need to be considered.

Recent work, linking approaches into a single modelling framework, and expanding the models to include the water-energy-food (WEF) nexus has been attempted. Two approaches have generally been applied:

- Incorporating more details into a single model structure [1, 2].
- Coupling models of different sectors and/or different temporal and spatial resolution by either soft or hard linking [7].

To date, although there have been some integrated modelling frameworks published in the literature, there has not been a comprehensive review of the advantages and disadvantages of these different approaches to policy evaluation. Furthermore, there has not been a review of model interactions, what inputs and outputs are required to link different models together and how these inter-linked models can address policy questions about the WEF nexus.

This review assesses the current state of combined and nexus modelling frameworks and provides a starting point for researchers looking to expand modelling tools to address the challenges posed by climate change, as well as presenting a framework for considering the best approaches to addressing the complex challenges.

1.1. Motivation

As the pressure to respond to climate change grows it is envisioned that more accurate and realistic modelling of responses and policies needs to be urgently considered [8]. This is of concern if compressed timescales for successful interventions for climate stabilization or normalization are to be realized while at the same time taking advantage of synergies and acknowledging and addressing trade-offs that will inevitably need to be addressed [9]. To date, modelling has largely examined linear policy responses that either ramp carbon pricing and/or hybrids with clean fuel standards and flexible regulations that inspire behavioural and rational economic decision-making behavioural change. Given the short response time available, it is anticipated that policies driving climate mitigation and adaptation solutions will need to incorporate performance or measurement feedback to ensure the necessary progress is achieved. This will require an increase in modelling complexity if assurance is to be provisioned to policy making community by the modelling community.

Each of the choices made to incorporate different model structures into a comprehensive framework requires trade-offs as well as decisions about which types of policy questions to address. A model that effectively addresses the interactions between land, water and energy may not be able to incorporate economic feedbacks that could significantly change the policy conclusions as well as technical aspects that affects practicality of the results. Although there are significant strengths in linking models, one must be careful to ensure that the linkages mutually enhance the different models being incorporated and do not exacerbate existing model weaknesses.

Many of the modelling frameworks used to date incorporate only two or three aspects of the broader system. As an example, the climate, land, energy and water (CLEW) framework [1, 10] considers only energy, land and water for both mitigation and adaptation but does not include considerations of other aspects such as impacts on health and overall well-being nor economic feedbacks. The Nexus Solutions Tool (NEST) framework [11], similarly, considers only the hydrological and energy impacts. The work by Brinkerink at University College Cork (UCC) [12] incorporates the land use and economic feedbacks.
of the MESSAGE-GLOBIOM model with a detailed power sector model but, again, does not incorporate health or water use in the analysis. The challenge, then, is to identify existing models that address parts of the bigger picture and to determine how to incorporate the strengths of these models into a comprehensive framework that can be used to evaluate the impact of policy decisions. How can we model the impacts of given adaptation and mitigation measures on outcomes on health, nature, the economy, water and land use and, overall, on the ability of humanity to live within the earth’s carrying capacity? How do we model the trade-offs between risks of environmental impacts in one area with the risks on human health, energy and economic well-being? What important model links need to be incorporated in a framework to ensure effective policy guidance?

1.2. Contribution

To address these challenges, we performed a detailed literature review on combining models to address more broad policy questions and held a series of expert elicitation focus groups to expand on the knowledge in the literature. This report documents three specific contributions.

- A formal literature review that provides effective guidelines for evaluating combined model structures for policy development. This enhances the ability of modellers to make effective modelling structure choices and provides guidance for future modelling endeavours.
- Expert elicitation focus group synopsis—groups of expert modellers utilizing combined models were convened and a structured discussion targeted at the benefits and challenges of combined modelling was undertaken. An additional benefit of these discussions was to increase the modelling community’s awareness of the need to consider the strengths and weaknesses of their chosen modelling approach.
- A modelling evaluation framework, based on the literature review and expert focus groups, that can be used to rank/review modelling approaches. This framework can also be used in the model planning stage to ensure that the most appropriate approaches are adopted.

The rest of this report outlines our findings. We start with a review of the motivation for this work in section 2, outlining the limitations of current modelling paradigms. This section also provides a conceptual framework for expanding model complexity which was used as pre-discussion for the expert elicitation focus groups. In section 3 we provide an extensive review of the literature on combined modelling, including a discussion of the concept of the nexus, how this concept has been applied in prior modelling, and what gaps remain for models to address. The outcomes and discussions from the expert elicitation focus groups are summarized in section 5 prior to providing a short conclusion.

2. Background

This section explores the complexities that need to be assessed and modelled by first reviewing existing modelling paradigms, discussing challenges with model linking/integration and finally noting challenges with expanding model complexity.

2.1. Existing modelling paradigms

As noted briefly above, existing modelling literature falls mainly into two knowledge silos: The power engineering community and the energy-economy modelling community. Within these communities three different models are generally applied, as noted in table 1; power systems models, capacity expansion models and energy-economy models.

The engineering modelling communities apply capacity expansion and power system models and focus on engineering solutions that replace the total primary energy supply (largely fossil fuels) with a predominately electrical system fuelled by intermittent renewables. Various approaches (Jacobson et al [13, 14], OSeMOSYS [15, 16], MESSAGEix [17], PLEXOS [18, 19] and GTMax [20]) have been offered which trade generation and storage combinations and technology choices (wind, solar, nuclear, biofuel etc). Power systems models (PLEXOS [18, 19] and GTMax [20]) optimize the operation of a given energy system once investments are determined (often by a capacity expansion model). These models are centered on assessing the short-term dispatch of energy technologies to ensure the system meets the reliability standards for electricity consumers. In general, they have high technical, spatial and temporal resolutions and often include intricate technological representations to ensure system stability and reliability. Capacity expansion models address projected demand changes to guide investments in future energy supplies. They generally optimize the investments in new energy capacity in a given energy system to meet growing loads based on available or anticipated future energy technologies. Exogenous predictions of demand growth, fuel prices trend, technology costs and policies are used to assess different investments. Examples of such models are MARKAL [21] and OSeMOSYS [22]. They typically have medium temporal (sub-yearly/seasonal) and spatial (regional) resolution and high technological detail.

Engineering focussed studies find the optimal/ideal outcome but do not consider the fully loaded cost of a reliable (always available) electrical generation system is significantly higher than the name plate capacity overnight costs that are often utilized for assessment of any given generation energy asset. Integration of variable generating assets into
systems also requires storage/flexibility assets and new grid lines to be developed, costs which often exceed the value of the capital cost of the basic generation asset [23, 24]. Energy security also increases costs if total availability and reliability are design requirements [25]. The cost of these solutions has not been generally accurately adopted by the energy-economy modeling community while feedbacks from energy-economy models are not generally included in most power engineering models. A further cost amplification that has not yet been considered is the impact of climate migration for a given geographic region. Renewable energy generation assets optimal for 2020 may be inefficient or even stranded with a change in regional climate over 30 years [26].

The energy-economy modeling communities on the other hand have focussed largely upon building models (CIMS [27], GCAM [28]) that permit the interaction of societal (individuals) choice behaviour with energy technology options and climate policy (carbon pricing, flexible fuel standards, carbon trading) to be assessed within the framework of a national or jurisdictional economy. The general assumption inherent in these macro-economic models is that the agents are price-takers, and that market equilibrium can be achieved. These models often rely on name plate capacity levelized cost of energy (LCOE) numbers from published sources such as those provided by the International Energy Agency [29], the US Energy Information Agency [30] and/or private organizations such as Lazard [31]. This pricing is often disconnected from the true cost of integrating new assets into an electrical grid, especially if system reliability is to be comparable to the current energy system (all sources of energy for a functional economy). Due to the broad scope of this type of model across many sectors of the economy, they generally have low temporal (multi-year time steps), technological (groups) and spatial (country-sized) resolutions to keep computational complexity manageable [20, 32].

Table A4, in appendix A, provides typical applications, strengths and weaknesses of the major models in the literature within each modelling paradigm for general comparison, including reference to a broader sample of models from [20, 41]. It should be noted that the classifications presented in these tables are not meant to be comprehensive, but to demonstrate the different computational tools used to address various political, operational and technical matters within the energy system modelling paradigms. Also, most models continuously evolve to address technological developments and policy shifts as well as to take advantage of computational and data-science advances, so some models may not fit neatly within a specific model paradigm or classification.

### 2.2. Model linking/integration

Recent published work hints at acknowledging these concerns but does not propose a specific formal framework. Work incorporating multiple sectors into a single model includes the CLEW systems modeling framework [1, 10], the NEST framework [11, 42] and work at UCC [12]. A CLEWS study for the city of New York found that decisions to increase energy efficiency in some cases increased water use and that decisions not considering these interactions led to inefficient use of resources [43]. When the NEST framework was applied to the Indus River basin in Asia it showed that the interlinkages between water and energy have significant policy implications [44]. The work out of UCC is not yet published but is showing how interactions between different sectors at a global scale can drive power system operations at the hourly scale [12]. In a similar vein Bieber et al [45] present a model of an urban energy system combined with an agent based model to evaluate the impacts of climate change on the provision of energy and water in Ghana and find that combining these models highlights the vulnerability of the power sector and the need for diversification. García-Gusano [46] link a life cycle assessment model to a power system planning model to incorporate life cycle impacts of the power sector. Focussed only on the power sector, Zhang et al [47] present a model that integrates a multi-objective optimization model with an hour-by-hour simulation model to enhance policy relevance. Although all these models are designed to enhance policy insights and trade-offs none critically review the strengths and weaknesses of combined models nor provide a formalized structure. Deane et al [7] used a similar approach to connect an Irish energy system model with an Irish power system model for a specific year. They find that the combined model significantly improves predictions of CO₂ emissions and costs of proposed scenarios in both models.
A fully integrated modelling environment could be defined as a model that allows migration of the total primary energy supply for a region to a reliable carbon neutral (or negative) system within an economic policy assessment tool that also includes an evaluation of the interactions of energy, water, food, natural and cultural security over a longitudinal period of climate change. Figure 1 illustrates a potential framework composed of a combination of existing modelling tools that allows these increased complexity issues to be examined.

Figure 1 illustrates the core concern. Ordinarily, energy-economy modelling tools or the broader integrated assessment tools will price the cost of renewable energy from a point source reference such as the Lazard LCOE indices or those provided by the International Energy Agency [31, 48]. These values are largely name plate capacity values. The concern is that these cost estimates do not accurately reflect the true cost of supporting increased energy demand to be supplied from the renewable energy sector as the impact of specific policies takes effect. The estimates do not include the cost of associated grid and storage requirements—nor costs incurred by specific geo-location engineering challenges. They also do not reflect the costs incurred by polices that limit or restrict the range of technical solutions that may be deployed. For example, nuclear energy may be an optimal technical solution for a particular jurisdiction but may not be a socially acceptable option. Thus, incurring additional costs for a less viable alternate. Biofuel is another example where the displacement of food crops for fuel crops may not be desirable. Thus, it is of concern that polices tested and examined may appear to address the challenges of transition to a carbon free economy, but because of the underlying cost errors they will not function with the expected efficacy.

It is also important to note that the diagram is somewhat simplistic for it assumes that the clean (non-emitting) electrical energy sector (nuclear, wind, solar, tidal and hydro) is the only investment area in which the LCOE requires a refined estimate. In practice the energy-economy modelling tools will employ a variety of LCOE estimates for alternate energy sources such as biofuels which are net-zero emitting fuels or traditional fossil fuels. The energy-economy modelling utility relies upon the relative relationship between these parameters as well as their absolute values to compute the behavioural response of a given society and economic region. These are the elasticities of substitution that drive behavioural choice between energy access options. Thus, multiple underlying energy capacity models could be envisioned.

Figure 1 also presents a proposed framework whereby the concern is addressed by linking an energy-economy modelling environment with a
capacity energy model so that for any particular jurisdiction and proposed policy a more refined energy cost can be generated by assessing how the required increase in demand could be met and its associated cost estimated. This linking of models creates a complexity issue. In general, the energy-economy modelling occurs in 5 year time steps, capacity modeling by contrast typically examines yearly time frames. And if power system reliability needs to be tested and challenged under duress for induced (climate or natural disaster) power demand spikes and robust engineering is assessed to consider climate migration for a region then an inner kernel of minute timescale power modelling should be considered.

This linking of two or three levels of modeling creates complexity issues that could lead to an unstable and unwieldy computing machinery that does not invoke trustworthiness for the end user and policy maker. To ensure that this does not occur, careful examination and discussion is required to ensure complexity is minimized. This could be achieved by abstracting the timescale modelling so that the linking information passed between the timescales is only the critical information that is parsed. Excessive passing of information leads to unnecessary complexity. Stability of the computational machinery could be ensured by simply soft linking the modelling tools so that longer time step economic analysis does not proceed to the next time step until the underlying information from the more granular capacity and power engineering models is provisioned. Similarly, the underlying models only proceed when a power demand for increased energy is requested by the upper layer economic modelling engine.

2.3. Expanding modelling complexity
In addition to expanding modelling to address the different temporal scales needed to incorporate economic challenges through to power systems stability, there is a need to expand models to fully address the challenge of wide scale biodiversity loss. Models need to address the Bonn Nexus which considers the interaction of food, water and energy security [49]. To fully address the challenges of biodiversity loss the need arises to include the interactions of not only these three sectors but to expand them to include natural security and cultural security. Natural security is a catch all for biodiversity, ecosystem services and functional global ecosystems. Cultural security emerges as an extension of the UNDRIP declarations. These considerations manifest as true costs in an economic model for the development of new energy assets will impact and force compromises between water, food, energy, natural and cultural assets. The development of the site C hydro dam in British Columbia, Canada, is a perfect example of how these five domains all interact and increase the costs for both the energy generation asset and the impacts (losses) of the remaining sectors. The inclusion of these five attributes (which we refer to as the Nexus-5) requires additional layers of complexity in the modeling framework depicted in figure 1.

Figure 2 illustrates that the energy-economy modelling will need to incorporate and account for the interactions to the Nexus-5 for an accurate assessment of any given policy. However, the question arises should these interactions also be subject to policy constraints or rules designed to enhance the rate of climate change mitigation at the expense of predetermined trade-offs. If so, the modelling complexities expand. Furthermore, policy and/or the output of the energy-economy modelling needs to inform the capacity energy modelling components of the preferred trade-offs within the Nexus-5 when geolocating a specific new energy asset. Identifying synergies between the sectors that can be exploited is also an important aspect of such combined modelling. These trade-offs and synergies, in turn, impact the values provisioned back to the energy-economy modelling.

These complexity expansions are amplified if the interactions of the Nexus-5 are unpacked to include intrinsic modelling and interactions of all 17 United Nation SDGs.

Although there are several examples where modellers have begun to incorporate elements of water, land use and climate change into their analysis, either by adding them to a single model or by combining models (see [50, 51] as examples), there is much work to be done. Most current energy system models consider only modest aspects of these interconnected systems. Figure 3 illustrates some of the evolving technical, social, political, environmental and financial interactions that need to be incorporated into energy system models for effective policy development.

3. Methodology
To address the modelling challenges and develop best practices we performed two major activities, a literature review and a series of expert elicitation focus groups. These two activities combined together to build the model evaluation framework described in section 6. It should be noted that these activities were undertaken in parallel, with the focussed expert discussions informing the literature review and highlighting areas to search for additional relevant papers while the literature reviewed allowed the authors to identify appropriate questions for the expert focus groups.

3.1. Literature review methodology
To fully access the literature on nexus modelling and combined modelling approaches the authors drew on their experience in the field to identify relevant articles to include in this review. These articles were augmented by citation searchers for specific articles
Figure 2. Including Nexus-5 modelling.

Figure 3. Interaction of technical, social, environmental and financial factors in the power system.
in databases such as Web of Science to ensure that the most recent and up to date literature on a given topic was identified. An iterative process of reviewing paper references and doing citation searches was used if it seemed additional papers of relevance could be identified. In total around 100 papers were read, with over 50 of these papers directly referenced in the literature review section or in the appendix with detailed model information. Articles included range from engineering to economics literature and also include some reports and gray literature.

Through this process, and the subsequent analysis of the articles identified, the authors identified themes in the literature and summarized the literature into these thematic areas: how the nexus of land, climate, energy and water is approached in the literature (section 4.1), how the modelling literature addresses combined modelling approaches (section 4.2) and how the nexus of land, water, energy and climate has been represented in existing modelling paradigms (section 4.3).

Given the broad ranging literature identified during the literature review process, and the divergent approaches between fields in how to address the challenges, this process helped synthesize the authors understanding of the nexus and combined modelling literature. To simplify the results tables in the body of the paper table 2 highlights specific model examples from the literature, with additional details for each provided in the appendix tables as appropriate.

3.2. Workshop methodology

Four workshops of 2 h duration were conducted. A total of 13 domain expert participants attended the four workshops. Attendees included representatives from countries around the globe including Australia, Canada, China, Europe, Uganda, the United Kingdom and the United States. Most attendees were modellers with an engineering or economics background working in academia, though industry representatives and policy researchers were also represented at the workshops. Of the modellers at the workshops, around half had done some aspect of nexus modelling or combined modelling in their research careers.

Each workshop was conducted in an identical manner and was comprised of four sections. An initial 10 min technical presentation was followed by two 45 min discussions. Each discussion was focussed on a key technical area with open-ended catalytic questions employed to initiate debate and encourage a wide gamut of exploration. The final session was a free-flowing discussion allowing the domain experts to voice and discuss core concerns that they felt had not been addressed in the workshop. All workshops were undertaken utilizing Zoom conferencing and recorded for later transcription. All transcriptions were stripped of personal attributions in compliance with the workshop agreements undertaken with the participants. Recordings were deleted upon the completion of this report.

The workshops were conducted in accordance with the predefined guidelines defined and approved by the Simon Fraser University Research Ethics Committee (approval number 202050280).

The introductory presentation was utilized in the workshop to set the stage for the following discussion sessions. A headline from a news story was utilized to capture the participants’ imagination and underline the purpose of the workshop. ‘California’s shift from gas to solar is playing a role in rolling blackouts’ [52].

The headline captures the zeitgeist within the ΔEP t energy modelling research team at SFU—that time frames for meaningful climate mitigation are rapidly compressing and that there is not sufficient time or resources available to tolerate policy and investment decision errors. Specifically, concern falls into two dimensions, energy infrastructure investment choices and the associated impacts upon food, water, human well being and biodiversity impacts. If so, is building more complex models that provision significantly higher fidelity (accuracy) of energy infrastructure costs, policy choices and performance for policy makers warranted? Furthermore, should these energy centric models be extended to include modelling of an expanded Nexus that includes water, food, energy, cultural (human wellbeing) and natural (biodiversity and ecosystem services) security. The nexus of these five attributes is a coalesced representation of the United Nations 17 strategic development goals. The fundamental goal of the workshops was to discuss how we can build effective decision-making tools that:

- enhance policy development;
- represent system complexities effectively;
- consider full system costs and performance;
- account for impacts on all areas of the SDGs/Nexus;
- incorporate interactions and feedbacks between the SDG/Nexus components;
- address system resilience.

Figure 4 was used to ask the participants to imagine a complex stratified modelling environment in which existing energy modelling tools that span different temporal domains are coupled to explicitly harmonize data transfer between the technologically explicit engineering reliability modeling tools to both capacity assessment and energy-economy modeling tools for utilization by policy assessment tools. The goal being to enhance fidelity in policy making and ultimately create easy to use, beneficial decision support tools. These domains are intrinsically linked in practice but predominantly modelled and assessed in isolation. The loss of precision and clarity of information transfer between domains being a prime candidate for error and bias in decision making. Participants
Table 2. Evaluating the representation of 1PstP order of direct linkages within the nexus of water-food-energy-land use-climate, plus economy.

| Model class          | Model class branches                                                                 | Water (W) | Food (F) | Energy (E) | Land use (L) | Climate (C) | Economy (Ec) |
|----------------------|--------------------------------------------------------------------------------------|-----------|-----------|------------|-------------|-------------|--------------|
| Energy-economy       | Base models                                                                          |           |           |            |             |             |              |
|                      | General equilibrium models (e.g. GEM-E3 and GTAP)                                    |           |           |            |             |             |              |
|                      | Partial equilibrium models (e.g. CIMS and NEMS)                                       | ✓         | ✓         | ✓          | ✓           | ✓           | ✓            |
|                      | Expanded versions                                                                     | ✓         | ✓         | ✓          | ✓           | ✓           | ✓            |
|                      | Climate-economy models (e.g. GCAM)                                                   | ✓         | ✓         | ✓          | ✓           | ✓           | ✓            |
| Capacity expansion   | Base models                                                                          |           |           |            |             |             |              |
|                      | e.g. MARKAL, OSeMOSYS                                                                  | ✓         |           |            |             |             |              |
|                      | Expanded versions                                                                     | ✓         | ✓         | ✓          | ✓           | ✓           | ✓            |
|                      | e.g. CLEWS                                                                            |           |           |            |             |             |              |
| Power system         | Base models                                                                          |           |           |            |             |             |              |
|                      | e.g. PowerFactory                                                                     | ✓         |           |            |             |             |              |
|                      | Expanded versions                                                                     | ✓         |           |            |             |             |              |
|                      | e.g. PLEXOS                                                                           |           |           |            |             |             |              |
were asked to consider if explicitly coupled models would ameliorate these concerns.

Consideration of figure 4 immediately invokes exploration in two dimensions; the complexity of model coupling and scope of model attributes. Figure 5 illuminates the complexity of different model coupling regimes while figure 6 illustrates the need to broaden the explicit energy-economy modelling components to include land, water and energy considerations and by further extension to include natural (biodiversity and ecosystem services) and cultural security concerns.

Figure 5 represents the spectrum of coupled modelling options. The diagram attempts to portray the existing uncoupled modelling approaches and how with explicit and implicit information links coupled models may be utilized. The diagram also attempts to convey that modeling complexity increases as various degrees of implicit and explicit coupling occur. The left-hand side of the diagram portrays the current utilization of uncoupled models where information is implicitly parsed between joint modeling programs, the information flow is regarded as soft in that it is often inferred and parsed by human and employed to confirm inferences. An increase in modeling complexity allows information theoretic links to be utilized that ensure rigorous (SI-unit compliant) information is parsed between models, perhaps between a capacity model and an energy-economy model. As modelling complexity increases explicit coupled models that parse information autonomously can be envisioned. Soft linking allows co-modelling to occur in which model attributes are confirmed or qualified during the process of discrete model runs between iterations of the paired modelling tools. Hard link coupled models implies explicit SI-unit information interchange between two or more models. The degree of complexity may be runtime encoded such that iterations of each model at each time step do or do not occur without confirmation from the coupled models. A slightly less complex approach is that after each complete modeling run the models communicate information results and re-run/iterate until all models agree. Both scenarios require complex runtime integration and sharing of information to execute.

This degree of modelling complexity envisions very explicit technology and attribute rich models offering detailed computational resolution and accuracy. Model transparency and fidelity is assumed but difficult to audit due to this high degree of integration and complexity.

Model complexity, as noted above, can also be expanded when attempts are made to include impacted systems that are adjacent to the core energy system. Figure 6 below illustrates the United Nation’s 17 SDGs—these have often been collapsed by the Integrated Assessment modelling community into the Nexus (3) that model water, energy and food/land...
trade-offs' and impacts as a function of public policy. Full scale explicit modelling of all 17 SDG’s is problematic because many goals do not lend themselves to mathematical or analytic representation. However, discussion to expand the nexus to include dimensions of natural and cultural security is warranted. Natural security is a reference term which envelopes eco-system services and biodiversity consideration that are independent of a simple agricultural land allocation. Cultural security is a term which recognizes impacts to peoples, often Indigenous, that may occur when specific energy, food/land, water and biodiversity trade-offs are invoked within a particular region as a function of public policy.

In summary, the introductory presentation posed two questions to the participants. Would an increase in modeling complexity that provisioned a high-fidelity decision support tool that was cost...
accurate and technical/engineering rich coupled with an integrated assessment environment that included the Nexus 5 attributes be worthy of development? Furthermore, would such a tool enable meaningful reduced risk policy decisions in an era in which rapid meaningful climate change response is required?

The core preposition was presented to the workshop as two distinct questions, the first discussion period focussed upon utilizing of highly coupled models for a technology explicit and attribute rich coupling of energy policy, energy-economy, capacity and reliability modeling. The second discussion focussed upon the inclusion of the United Nations 17 SDG’s coalesced into the Nexus 3 or Nexus 5 framework.

In summary, the literature review and the expert elicitation focus groups provide the foundation for our recommendations in section 6.

4. Literature review

As the expansion of modelling complexity covers a wide range of topics, so does this literature review. We start with a deep dive into the Nexus concept and how it is defined in the literature in section 4.1. Section 4.2 provides an overview of how combined modelling has been applied to date. Section 4.3 provides a discussion of how the Nexus has been represented in different modelling applications.

4.1. Nexus approach in the era of low-carbon economy

Global demands for water, food and energy are predicted to increase by about 50% by 2050 with respect to 2020 under the business-as-usual scenario due to the impacts of climate change, urbanization and population growth [53]. As the concern for the security of these resources increases, a call for a coherent analysis and integrated resource management is gaining more attention in the research and policy communities. The nexus terminology gained popularity after the World Economic Forum in 2008, where the challenges within the economic domain were examined through their affiliation with climate change, water, food and energy perspective (WEF nexus) [53]. However, moving the nexus concept forward from theory to practice proves to be problematic as there is ambiguity in its definition, disagreement upon its main components as well as how the interactions between them are functioning (e.g. [51, 53–55]).

Note that much of the nexus concept related literature focuses on supply and demand optimization, overlooking the importance of political, cultural and social actors (nexus governance) influencing the allocation of resources and political decisions [54, 56]. Figure 7 illustrates the interactions and pressure on the nexus that have been identified within the nexus literature. Many of these factors and their linkages are not yet well represented in the energy systems modelling domain. As the models are intended to inform policy makers about the trade-offs and benefits of their decisions, the absence of these critical considerations and linkages means that they are sometimes overlooked in policy recommendations. The red dashed circle in figure 7 represents the status quo, where the components (black circles) of the nexus system function at nominal utility with no change in endogenous or exogenous pressures. A black net (tensile web) represents interdependency and interactive relationships between these components; the status quo represents an equilibrium of the endogenous pressures within the system.

In general, the term ‘nexus’ is used to indicate the interactions among interdependent components [53]. For instance, the water-energy nexus refers to interdependency and interaction between the water system and the energy system. ‘Nexus’ indicates that failures in the management of one component may impose pressure on the availability or functionality of other interdependent components. The nexus approach helps to recognize and reduce the potential trade-offs among interdependent components when it comes to policy-decisions and investment. Biofuel is a clear example of this dynamic. Biofuel energy has gained increasing attention as a climate change mitigation strategy. However, increasing the role of biofuel energy puts pressure on the food system as competition for water and land use emerges; furthermore, natural security may be pressured due to the potential biodiversity loss [57].

The goal of modelling nexus systems is to safeguard the resiliency of the whole system by creating feedback loops between endogenous and exogenous components of the system. Resilience refers to the ability of a system to keep functioning within defined bounds and its capability to endure during and after a severe shock [58]. Qualifying and mathematically expressing many of the nexus components and their interactions is a challenging task, especially those within the social and environmental domains. Models that support policy decisions often evaluate trade-offs and benefits of long-term decisions based on monetary values. As a result, many essential interdependencies, such as health impacts, natural security (e.g. biodiversity), individual wellbeing and cultural values, are missing from models. These models are often partial (sectoral objectives are not equally weighted) in their analysis as they mainly represent water or energy-centric perspectives [59].

There are also unpredictable and once-in-a-time events that exogenously put pressure on the nexus and test the resiliency of the system. These extreme events come in various forms: social movements, natural disasters (e.g. earthquake), game-changing technological breakthroughs and the sharp edge of political ideology. The 2020 coronavirus epidemic is...
an example of such an event that has created sev-
eral social, political and economic changes, such as
the investment trajectory within the petroleum
and renewable energy industries, as well as indi-
vidual behavioural transitions in using public trans-
portation. These unpredictable exogenous elements

Currently, most models used for long-term plan-
ing (e.g. energy-economy models) are incapable
doing these extremes or capturing the polit-
ical, social and cultural factors (as determinants of
change) in their analysis. However, the fact that there
are interdependencies that defy mathematical defin-
itons or predictions based on traditional analysis
methodologies does not mean they should not be
explored in the models and future scenario simula-
tions. Several energy models have tried to incorpo-
rate nexus elements into their analysis in the past
decade, either by adding them to a single model or by link-
ing models. The next sections of the paper evaluate
representations of the nexus approach in the existing
energy system modelling paradigms.

4.2 Combined modelling approaches
As table A4 (appendix A) indicates, different energy
models are designed to help address various ques-
tions regarding the policy, investment and engineer-
ing decisions. Because of this variety of purposes, they
have various temporal and operational resolutions.

4.2.1 Combined the capacity expansion and power

system models
Providing capacity expansion models with the reliabil-
ity, flexibility and grid security constraints estimated
by the power system models have proven to be use-
ful in informing decisions on power planning, policy
and new capacity expansion investments [60]. Capacity
expansion models provide a long-term high-level
trajectory of the evolving power system, reflecting
both operational and investment considerations [60]. However, due to the computational limitations, capacity expansion models generally employ a simplified form of dispatch system criteria (operational resolution) by, for instance, aggregating similar plants or using a limited number of time slices per year/season in their long-term simulation. Power system models, in contrast, are rich in system operational details; they represent individual plant, unit commitment and system dispatch at high temporal and spatial resolutions. However, they are limited in projecting the power system evolution over time [60] as their focus is on keeping the current system stable.

As the decision to expand the capacity of variable renewable energy supplies is determined by the geographical, meteorological and specific operational elements, efforts have been made to combine the long-term investment and short-term system operation domains to assure the reliability of the power system in future. In 2015, Diakov et al [60] created a Linking Tool (framework) that translates a capacity expansion model output into a power system model input. For their work, they combined the ReEDS capacity expansion model and the PLEXOS power systems model. The goal was to provide a tool for the power system models with a systematic method of embracing the long-term expansion projections; for instance, translating the regional aggregated structure of plant representations in ReEDS outputs to individual power plants’ new capacities in PLEXOS as inputs using optimization methods [60].

Diakov et al [60] suggest that using the Linking Tool to combine the capacity expansion and power system model’s strengths helps capacity expansion models better represent the variable renewables. The power system model’s operational input helps establish a more adequate aggregated form of the unit commitment and dispatch system for the capacity expansion model. It can also help to simulate more in-depth projections of the detailed system response of the power system to regional policies. The output information from the ReEDS (capacity expansion model) that was transferred into PLEXOS in this work was mainly the location, type and capacity of new and retired generators. Their work shows that the combined model is better equipped to investigate the effect of various aspects of choosing between renewable energy options in a case of high levels of renewables in the system [61].

Deane et al work [7] is another example of combining high-resolution power system models with capacity expansion models. In their research, an Irish capacity expansion model (using TIMES) was combined with a power system model (using PLEXOS). The goal of the combing approach (soft linking) was to better understand the practicality of the capacity expansion model outputs on the electricity system operation. The focus was on examining the suitability of features such as the system reliability and flexibility, renewable energy generation curtailments, and CO₂ emissions reduction calculated by Irish TIMES. The linking was a one-way flow of information sending TIMES outputs (electricity generation portfolio, fuel prices and carbon prices) to PLEXOS. They used an optimized power portfolio for a specific year from Irish TIMES outputs and ran a detailed high-resolution simulation of the same portfolio in PLEXOS with high operational considerations.

The result of the combined modelling approach by Deane et al [7] confirmed the reliability of the simulated electricity generation portfolio created by TIMES. However, their work showed that in the absence of the power system model’s detailed technical constraints, there is an inconsistency in assessing flexibility and calculation of the CO₂ emissions reductions. The detailed unit commitment and dispatch analysis in PLEXOS showed a significant difference in the technical parameters such as various generators’ capacity factors, start costs and technical curtailments of renewable energy generation. The results also showed that the conventional energy-economy system models tend to underrate the importance of system flexibility (namely storage). They underestimate the curtailment of the renewable energy sources (in this case, wind power) as underestimating the amount of CO₂ emissions calculated during the energy transition period. The limitation of their methodology is the assumption that the historical data can represent a future variable renewable energy supply portfolio.

4.2.2. Combined energy-economy and capacity expansion models

There are few examples of combining energy-economy models to capacity expansion or power system models in the published literature. Europe seems to take the lead in this approach. When the European Council set ambitious targets in 2014 to reduce their greenhouse gas (GHG) emissions by 40% by 2030 (in comparison with 1990 levels), energy-economy modelling was used to project the economic and technological pathways of meeting this target [32]. The results indicated a need to increase the share of renewable energy sources (mainly solar and wind) in their energy supply by about 10%. In 2015, Després [62] combined an energy-economy model, POLES (prospective outlook on long-term energy systems), and power system model, EUCAD (European Unit Commitment And Dispatch) to evaluate the impact of such a move on the flexibility of the power system. Després recognized that in the simulations done by energy-economy models like POLES for Europe, the impacts of wind and solar variability, ‘…was only taken into account through a maximum wind penetration, linked to the availability of other dispatchable sources, and through a balancing cost correlated to the wind penetration’ [62]. These assumptions may profoundly influence the accuracy of the simulation’s
outcomes, mainly in the area of operation costs, system flexibility and energy expansion investments. One of the unique aspects of this work is the two-way coupling methodology to exchange information back-and-forth between POLES and EUCAD directly.

In Després’ work [62], EUCAD received all its main inputs from POLES simulation for a specific year such as, ‘…load, variable costs, installed production, storage and interconnection capacities, energy available for dispatching and energy to produce from electricity’ [62]. Then the generator-by-generator unit commitment and dispatch analysis and other production curtailments from EUCAD outputs will be aggregated to match the temporal resolutions of POLES. Després’ work reflects the importance of having operational details in creating a reliable and realistic projection of technical and economic challenges in the integration of a high share of variable renewable energy sources in the power system. This is specifically important in projecting the role of storage, overestimating the value of backup services from base-load fossil fuel sources (coal in European context), the renewable energy operational curtailments, flexibility options and investment directions in the pool of technologies.

In 2017, Collins et al [32] used a combined modelling approach to verify the result of a 2012 reference scenario developed in PRIMES to project the European energy system portfolio of 2030 (later extended to 2050). Collins et al’s work was focused on validating the curtailments of having high renewable energy generations in the system as well as levels of interconnector congestions, and wholesale electricity prices. They combined (soft linking) two models of PRIMES (EE model) and PLEXOS (PS model). The main challenge was the disaggregation of installed generation capacities developed for each Member State in PRIMES to reflect geographical and operational details required in the power system model.

Collins et al [32] investigation demonstrates that detailed operational analysis gained by coupling the power system and energy-economy models could capture elements that are not otherwise represented in the long-term energy system decisions. For instance, in the least cost dispatch simulation, PRIMES overestimated the potential share of variable renewable power by 2.4% in comparison with PLEXOS output. In addition, as the energy-economy models are not able to fully capture variable renewable curtailments and interconnector congestion, PRIMES demonstrated overly optimistic results about the flexibility of the power system with a high level of variable renewable power, underestimating the value of flexibility measures such as demand response and storage options (power to gas, power to heat and pumped hydro).

Table C6, in appendix C, summarizes the objective, flow of information, main findings and challenges of the combined modelling examples discussed above. As shown, increasing the temporal and operational resolutions of energy system models is a fundamental part of transitioning toward a system with high penetration of renewable energy generations and a vital step toward incorporating the nexus concept within climate action-related policies. Examples in table C6 (appendix C) highlight the benefits that can be gained from generating the flow of information between energy-economy, capacity expansion and power system models.

4.3. Representation of nexus concept in the existing models

As described in previous sections, the core of the nexus concept is the integrated management of resources such as energy, food, water, etc. However, to close the gaps from theory to practice and develop a model that can serve policymakers, the impact of political, cultural and social actors (political economy), as determinants of change, needs to be included in the models [54–56, 63, 64]. The nexus approach acknowledges that all these components are interrelated and interdependent systems, and if they are modelled in isolation, critical trade-offs will be overlooked in policies targeting climate actions and transition to a low-carbon economy. Among economic sectors, energy is the main driver that controls the future pace of GHG emissions. As a result, the previous sections of the paper focused on the limitations of existing energy system models in representing the energy transition aspects, mainly the flexibility and reliability of the grid with a high penetration of intermittent renewable resources. This section maps the gaps in the representation of the cross-disciplinary and intersectoral linkages required by the nexus concept within the existing energy system models.

Even though the importance of the nexus concept has been noted in the literature for almost a decade, its implementation within the modelling domain has not been rigorously defined. Lately, nexus considerations have been broadened to expand beyond the traditional three nexus dimensions of water, food, energy to create a more realistic representation of the world (e.g. [54–56, 63, 64]). Climate, economy, minerals, land use, health, biodiversity security, waste and technological advancements are examples of other dimensions [50, 65].

In 2016, the European Commission piloted 12 case studies across Europe (SIM4NEXUS project) in various spatial resolutions to better understand interlinkages and interactions within the five nexus dimensions of water, food, energy, land use and climate. One of the outcomes was the creation of the nexus tree approach to guide modellers to systematically recognize the direct and indirect interrelations within the nexus system [50]. In this approach, the direct linkage between two components (e.g. energy and food) refers to the impact of a change in the status
of one of the components (e.g. food) on the status of the other one (e.g. energy) without interference from the rest of the components (e.g. water, land use and climate). Note that energy-food linkage (E → F or EF) refers to the effect a shift in energy status has on food production, which is entirely different from the impact that a change in food status can impose on energy status (F → E or FE). Accordingly, 20 direct interlinkages can be recognized in the five-dimension nexus defined in SIM4NEXUS project as [50]:

- water: WF, WC, WL, WE;
- energy: EW, EC, EF, EL;
- land use: LE, LC, LW, LF;
- climate: CL, CE, CW, CF;
- food: FC, FL, FE, FW.

Following this analysis, the indirect linkages are defined as the interaction of two components through a change in a third [50]. For instance, EWF (E → W → F) refers to the indirect effect of a change in energy status (e.g. increasing in energy production) on the food production due to the competition of both components for water (i.e. water availability in the area). The full set of interconnected linkages for the energy system are shown in figure 8.

A similar nexus tree diagram can be centered around each of the nexus components to explore all the interlinkages. Figure 9 shows all the direct and indirect ways that a change in energy status can impose on water status and vice-versa.

Following the tree nexus approach, table 2 is developed to investigate the representation of nexus components within the existing energy system model classes (energy-economy, capacity expansion and power system models). Table 2 explores the quality of linkages and maps the current gaps within the existing models.

Much of the nexus concept-related literature and models focus on supply and demand optimization between water, food and energy resources (WEF nexus), thus overlooking the importance of other components and political, cultural and social actors influencing the allocation of resources and political decisions. These extra components are largely missing from the modelling domain; thus, they are excluded from the table 2 evaluation. Examples of the main missing components are culture and health, waste management, minerals, biodiversity and emerging technological advancements.

Some models include some aspects of the nexus components such as water policy impacts (e.g. restrictions on water usage). In general, most of these linkages do not qualify as dynamic as envisioned in this report. Checkmarks in table 2 indicate that the model class often tracks the requirements of the ‘A’ component (e.g. food) interaction with the ‘B’ component (e.g. water) in the AB linkage (A → B); also, it represents the interdependent competition between these two components. To illustrate, the checkmark in the food → water (FW) column indicates that a model weighs water status in assessing choices such as

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**Figure 8.** Nexus tree approach: direct and indirect interlinkages of energy with other components of five-dimensional nexus of energy, water, food, land use, climate. Reproduced from [50], CC BY 4.0.
technologies options, crop type and land use within the food dimension (direct and indirect linkages to water).

The ideal model from the nexus perspective would have checkmarks in all sector combinations. That means to represent the nexus concept truly, the linkages between components need to be established both ways. For instance, to represent the full nexus integration of water-energy interaction, a model needs to establish a close (endogenous) feedback loop (both WE and EW) between these two components. Such a feedback loop covers all the direct and indirect linkages shown in figure 9.

As most models continuously evolve to incorporate more details in their analysis, there is some overlap between the areas covered by different models. Thus, some models may not fit neatly within a specific model paradigm or classification. In table 2, each model class is therefore divided into two branches of the base model and expanded versions to bring more clarification into the matter.

4.3.1. Energy-economy models
As discussed in previous sections, the energy-economy models simulate the human utilization of energy commodities and resources using a market equilibrium setup. They operate either on a general equilibrium or partial equilibrium basis. As indicated in table 2, this difference in the operational approach is seen within the energy to the economy (E → Ec) linkage. In the energy-economy models operating on a general equilibrium basis, energy use and prices influence economic indicators within the model (e.g. GDP, employment, investment, aggregated consumption), as reflected within the nexus concept.

However, in partial equilibrium models, energy sector status does not impact economic indicators within the models as they are taken exogenously. Note that although many energy-economy models indicate that they broaden their scope beyond the energy sector to other sectors of the economy (e.g. agriculture, heavy industries), their inputs are often provided exogenously or are there as tracking only data (e.g. tracking aggregate CO₂ emissions). As a result, the linkages do not qualify for the nexus approach. CIMS, for example, provides all its feedstocks such as energy demand, agriculture (F → E, such as biofuel sectors), GDP, transportation and inputs from heavy industries exogenously rather than inbuilt strings needed within the nexus concept [66].

The extended versions of the energy-economy models often accommodate energy-climate interactions within the model’s analysis. This allows the examination of the impact and costs of climate change and climate action policies (e.g. GCAM). As shown in table 2, the extended version models incorporate more direct linkages of the nexus approach in their analysis. For instance, in the food dimension, indicators such as future commodity prices and future profit rates (F → Ec) are endogenous feedstocks, while current commodity price, productivity, growth rate, annual harvested area and cropland are fixed factors (Ec → E and F → L) [67]. Note that in order to have a closed-loop interaction as determined by the nexus approach, the two-way linkage is required (e.g. both $E \rightarrow Ec$ and $Ec \rightarrow E$).

4.3.2. Capacity expansion models
The focus of capacity expansion models is to optimize the costs of future investments in energy sectors. As shown in the table, the base model in this class only includes energy to climate linkages as they are tracking the amount of CO₂ emissions for different technological and capacity expansion options. All the economic and technological information, such as energy demand and technology options, are exogenous inputs; consequently the base models of this class do not interact with energy pricing [51].
CLEWS is chosen as an example of expanded versions of capacity expansion models. The model focuses on assessing interlinkages between resources of climate, land (food), energy and water systems [68]. It is developed based on the sustainable development (SD) concept, and as a result, several aspects of the nexus concept are incorporated within the model. The significant differences between CLEWS and models like GCAM are in their underlying philosophy or purpose behind designing a model (simulation vs optimization) and the economic component. As shown in table 2, the economic competition linkages are all missing in both the basic and extended version of the capacity expansion models (e.g. Ec → E and E → Ec).

4.3.3. Power system models
From a nexus representation standpoint, the power system and basic capacity expansion models both have almost a similar built-in linkage (E → C), but their analysis is based on different temporal resolutions. The power system models are centred on assessing the short-term dispatch of energy technologies to ensure the system meets the current demand with current available capacity. Thus, incorporating other components of nexus is out of their scope.

4.4. Literature summary
As discussed in previous sections, energy system models vary in their temporal, technical, spatial (inter-sectoral) and nexus (cross-disciplinary) representations. While no single model currently has the capability to fully represent the nexus concept, combining modelling techniques can be beneficial in addressing the limitations. Regarding the expansion of the intersectoral coverage, table A4 (appendix A), table B5 (appendix B) and table C6 (appendix C) demonstrate the variety of the policy and investment questions that each class of energy system models can address (underlying design philosophy), as well as a range of temporal, spatial and operational resolutions that models in different classes are designed to operate. The results of various case studies, show that in a system with a high penetration of variable renewable energy generation, the lack of sufficient operational details and low temporal resolutions within the energy-economy models leads to an inaccurate estimation of energy transition cost due to an overestimation of the value of the baseload technologies and variable renewable power generations [32]. It can also lead to underestimation of the value and importance of technologies helping to create a flexible energy system (e.g. storage). These inadequacies may mislead policy decisions and, consequently, the flow of investment in promoting new technologies and future power capacity plans. A lack of high temporal and operational details in energy-economy models can also lead to an underestimation of the overall cost of meeting long-term emissions deductions targets [32].

As highlighted in table B5 (appendix B), the level of detail of energy system models varies considerably. Although increasing the level of temporal resolutions in a single energy-economy model is suggested as effective for systems with larger shares of variable renewable energy sources [7, 61], due to the broad scope of such models, this approach may not be able to capture the full scale of flexibility and operational curtailments required within a system with a high penetration of variable renewable energy generation. Overlooking the operational considerations affects the ability of energy-economy models to determine factors such as increasing the generation capacity or determining the timing of investment in new technologies.

5. Expert elicitation focus groups
Building on the literature review on combined modelling, a series of expert elicitation workshops were convened. The workshops engaged energy modelling domain experts from all energy knowledge arenas (technology, economics, public policy development) to participate in a broad discussion focussed upon the potential of coupled modeling environments to link domains for enhanced policy and guidance outcomes. This section provides a summary of the main discussion points brought up during these workshops.

5.1. Summary: best practices for increased energy and energy-economy modelling fidelity
A resounding response in all four workshops posited that there were more advantageous directions for research than purely focussing on and pursuing combined modelling. A predominate concern was that model complexity and model management has already reached a level of complexity where model fidelity, transparency and trustworthiness is being questioned as the underlining model assumptions are hard to decode and audit. Rather than pursuing further increases in model complexity, an overwhelming consensus amongst the respondents promoted utilizing collections of models that are sufficiently purposeful and trustworthy to help explore scenarios and most probable outcomes emerged. Flexible purposeful models yielding intelligent guidance and valuable solutions of trustworthy providence in a responsive time frame were deemed far more valuable.

A secondary concern with combined modelling was that the time and expense taken to develop and verify such an all-encompassing modelling tool that could pass comprehensive trustworthiness tests would most likely be prohibitively expensive and take far too long to develop; thus, precluding a meaningful role in defining policy for responding to the urgent and now compressed climate mitigation time frames.

Despite these criticisms the opening preposition did catalyze robust conversations on how to achieve the desired goals in provisioning policy decision
support tools through utilization of existing models and enhancing working practices. Specifically, open-
source models were strongly encouraged because industry black box models have become over complex
with ill defined or un-auditable assumptions built in. The nature of these models is such that they foster a
sense of overconfidence in their projected results, especially among decision makers who may not have
deep technical literacy. Open-source models that are subject to wide scale scrutiny received wide scale sup-
port in the discussions as a primary tenet for model trustworthiness and purpose.

Open-source models free of cost would encourage inter team collaborations where experts in differ-
ent fields from different backgrounds could inter-work in a functional collaboration exploiting insights and
data sharing framed in common intellectual/conceptual platform. This statement rests upon a second import-
tant tenet that the modelling assumptions are harmonized and consistent between model-
ners and domain experts. OSeMOSYS and the CLEWs platforms were often cited in conversation as an emer-
gent example. Against this backdrop a 'culture of defining the intended purpose and use' of any given
modelling collaboration was deemed a critical attrib-
ute against which results could be judged/framed. Furthermore, recognizing that models (standalone or
coupled) are abstracted representations of far more
complex real-world systems and as such there is a
limit to their utility. The models will only reveal attributes of the properties and the relationships
between attributes that was fundamentally encoded.
They will not reveal new, novel and non-obvious rela-
tionships that are not intrinsically encoded, though
they may reveal unexpected interworking's between
the encoded and attributes and relationships. This is
a critical bound that needs to be conveyed to those
that utilize/consume the models’ output.

A third tenet that emerged from the discussions was that stakeholder outcomes, i.e. policy makers,
should be involved throughout the modelling process to both engender understanding of the model, inform
correct use and purpose and ultimately build trust-
worthiness in the model outcomes. Furthermore,
inclusion of lead agencies to ensure providence of
input data sets was deemed critical.

In addition to these high-level conceptual argu-
ments practical inferences for coupled modelling
emerged. Specifically, most modelling teams and by
extension inter-agency or inter-institution modelling
collaborations would be well advised to adopt the
rigorous standards of industrial software engineering
practice. Namely:

• Standardization: clear routines, interfaces and
automated processes for data handling, including
agreed-upon metrics for shareability.
• Documentation: keeping track of what has been
done and how to avoid having to re-do work.

Software experts documenting and organizing
code.

• Model input and output synchronization: using
master templates from the beginning, including
variable names and output formats.
• Matching metrics: current metrics do not, neces-
sarily, match the increased complexity of the sys-
tem.
• Focus on accuracy and usefulness: combining
models can cause a lack of accuracy and therefore
usefulness. Start large-scale and model to derive
useful insights. Making a decision sometimes does
not need high accuracy.
• Soft links (example with electricity, transport and
heating and cooling) can be done quickly, but can
be challenged by discrepancies between models.

Figure 10 illustrates our view of the complexity
map which echoes the nuances of the first discus-
sion topic held during the workshops. The diagram
places both the initial preposition and the resulting
technical recommendations on a plane of increas-
ing complexity. The two dimensions correspond
to increasing the complexity of specific/individual mod-
els and increasing the degree and level of complex-
ity of coupling between models to interwork. As
stated in the previous short summary the preposi-
tion of increasing modeling complexity to form an
integrated single model that enhances policy fidel-
ity was rejected. Recommended responses argued for
increased 'quality of practice' and 'utility awareness'
within the blue zone of existing complexity.

Importantly, exploiting different coupling com-
binations amongst a collection of capacity engi-
neering, reliability engineering, energy-economy and
integrated assessment models allows for a much
broader range of policy proposals and scenarios
to be examined. The counterpoint development of
a single highly integrated complex model will to
some extent self-limit the number of research ques-
tions that could be explored. This occurs because
with increasing complexity, flexibility is diminished.
Thus, enhancing working practice around struc-
tured coupled model research was deemed far more
valuable.

The following subsections reflect detailed discus-
sions and recommendations for operation of coupled
models within the blue complexity region which util-
izes existing models. The topics range from the need
for mundane software documentation and design
practice to working and research methodologies for
trustworthy coupled model investigations.

5.1.1. Basic model construction observations
Currently many models are private corporation
closed black boxes or very poorly documented and
potentially architected open-source models that
are forced to operate in a 'club' model in which
apprenticeships with proficient tutors/users is really
In acknowledgment of this prevalent weakness the workshop respondents strongly recommended that existing models are sufficiently complex to represent existing energy economies and systems to provide good policy testing and scenario exploration. However, it was strongly recommended that migration to true open-source offerings with clear documentation and training packages so that new users and policy stakeholders can quickly gain confidence in and readily audit the model be achieved. Furthermore, given the gravity and global impact of climate policies it was felt strongly that open and transparent architectures are a 'democratic responsibility' because the guidance they offer impacts all global citizens and confidence that there is not private or industrial bias and opportunity built in is a fundamental tenet of unbiased policy development.

The scale of this endeavour immediately elicits the need for collaboration between experts in different fields and modeling approaches. Collaboration is deemed critical if the divides between different sectors and standalone models is to be breached. The need for functional interdisciplinary teams is very evident but the cost in time and organization is not to be underestimated. This is particularly true at the software construction level for the array of different IT skills needed to navigate the interfaces between models and languages will be considerable. These challenges can be exacerbated when technical details are not readily discerned or are missing.

To support this endeavour, it was deemed necessary that the standardization of software routine construction, interfaces between models and internal model architectures should be employed. Furthermore, automated process should be utilized where possible to ensure operational consistency. Efforts to systematically standardize scripted workflows, data definition and metrics should be taken. These efforts would allow new users to rapidly assimilate the use of the models into their investigations, audit and critique and report thereby fostering confidence in the model and confirming model fidelity and utility. Furthermore, such efforts readily allow for modelling extensions and third-party contributions to be integrated.

Adoption of the IT industry’s standard software documentation techniques was strongly recommended. This is a broad recommendation covering all aspects of model development from code architecture to the foundations of coding templates for individual routines. Documentation should also include verification and testing scenarios that allow baseline model behaviour expectations to be set and quantified.

If these basic practices are adopted, then the integration of soft or hard linked coupling of existing

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**Figure 10. Discussion complexity map.**

- Simplified single model studies
  - Good for examining model behaviour
  - Limited use in practical applications
- Increasing Model Coupling
- Increasing Computational Complexity
- Machine Model Coupling
- Increasing Complexity within the same model structure
models could proceed with a much higher level of confidence.

5.1.2. Coupling models
Extending the range of questions and policy options that can be explored by coupling models was welcomed by the workshop, but caution was offered with respect to the mechanics of coupling models. Specifically, much like the previous subsection's recommendations, good working practice, standardization and documentation was pressed. The logical extension of these comments where that when coupling models, it would be imperative to harmonize the input and output variables such that numerical consistency and SI unit definition is accurately maintained between the models. This would be aided by systematic variable names and formats. Automated workflow scripts to ensure execution order of coupled models is strictly maintained between observational runs and is not subject to logical inconsistencies due to human error was strongly advised. This supports reproducibility and the option of regression tests to be conducted to ensure data corruption and/or model coupling sequence errors have not incurred.

5.1.3. Coupled model utility and methodology
As the complexity of policy and scenario exploration expands by utilizing multiple models, and the coupling/transfer of information between, concerns arise with respect to overall results integrity. Specifically, the utilization of metrics and data and the context to which they are understood by policy decision makers and the utility within the model(s) needs to be understood and be logically consistent between and within each utilized model.

A specific example is the LCOE metric, LCOE, familiar to policy decision makers and often central to scenario studies in energy-economy and integrated assessment models. However, in the context of capacity engineering and reliability analysis, the LCOE of solar for example can be very misleading for economic policies based on the assumptions of technology LCOE costs can falter in a capacity expansion model that needs to allocate storage capital assets for non-solar resource availability time frames. These unexpected cost increases are not captured in energy-economy models for example, and as a consequence, there is a disconnect in policy construction and the true real-world impact when total system cost of renewable generators and storage costs dwarf the modeled cost. Historically, the LCOE metric for fossil fuel technologies that offer energy on demand would be consistent between capacity expansion and energy-economy models. This is not true when intermittent renewable technologies are selected. Additional ‘hidden’ costs of storage are lost. Thus, the need for careful examination of all metrics and shared information flows between models in a coupled modeling exercise need to ensure that internal, shared and external utilization of metrics is logically consistent across the entire modeling paradigm.

Furthermore, these issues could compound in situations where coupled models are utilized that work in different time frames. Consider a scenario when 10 min fine grained capacity analysis models are used for enhanced energy cost modeling with an integrated assessment tool that operates at early time intervals over a 50 year time span. Ensuring logical and mathematical consistency is of paramount importance if trustworthy coupled models for policy and scenario exploration are to be created.

The consideration of metric and information consistency leads to a more philosophical debate of overall accuracy considerations and how the drive for precision, via extended complex models or coupled models, leads to a false sense of ‘value’ because the opportunity to ensure that the interaction of the systematic mechanisms of energy economies and engineering models gets perturbed and may not be accurately represented. Consequently, scenario analysis becomes paralysed by a lack of internal systematic consistency in a manner that is hard to detect. Workshop participants very much felt that models that were sufficiently purposeful (not overly complex) that could be utilized in standalone or coupled modes should be used so that the logical consistency of scenario outcomes could be audited/cross checked. This invokes a sense of trustworthiness and utility amongst policy developers as opposed to the nagging doubt associated with the utility of relying upon a complex black box that cannot be audited.

Purposeful, trustworthy coupled models that could be utilized in a guided dual expert (human and machine) policy scenario exploration role were deemed to be most valuable by the workshop participants. Thus, decision support tools were very much supported, rather than explicit complex representations of the real world which at best are still abstractions.

5.1.4. Modelling purpose
The notions of purposeful, trustworthy and accessible models were frequently referenced in the discussions and collectively summarised as ‘fit for purpose’. This notion forces the users and developers of the model to think very carefully about the balance between technology explicit detailed representations for numeric precision and the interactions of large system dynamics. If the purpose of these models, coupled or otherwise, is to ultimately provision informed policy decisions that create meaningful change, then a significant portion of effort should be focussed on ensuring that the large-scale interdependencies of economies and engineering are well represented and not sacrificed by overwhelming focus upon numerical accuracies. The endeavour is to provision insight into
policy outcomes and not specific numeric data values, rather, the relationships between policy inputs and end outcomes is far more valuable. The models are tools of future exploration and communication that allow policy ideas to be road tested prior to being codified.

It was felt the use of existing models coupled carefully to explore a wider range of scenarios would be a valuable endeavor as opposed to the original preposition of highly coupled models that were very technologically detailed and ultimately narrow in modeling scope. A flexible modeling framework allowing different models to be interconnected for examining a broad range of different policy options was deemed an intriguing possibility.

Finally, it was felt that it is very important to identify what issues the model cannot offer insight into. This is an especially important observation when utilizing the models to inform end use agencies of possible outcomes when considering specific potential policy drivers. Furthermore, engagement with lead agencies to ensure input data providence is a critical component when offering insight into potential outcomes.

5.2. Summary insights: best practices for inclusion of nexus and SDG attributes

The second directed conversation in the workshop was focussed at how to include the United Nations 17 SDG’s within the framework of energy-economy and capacity expansion energy coupled models. The goal of creating such a modeling framework would be to allow policy options to be examined, exploring the impacts and opportunities upon adjacent and connected resources. While many of the SDG’s do not lend themselves to analytic or codified representation, the Bonn Nexus-3 developed in 2008 provides a framework for water, land/food and energy considerations to be examined [49]. The workshop proposed the expansion to the Nexus-5 which additionally includes Natural and Cultural security. As with the previous discussion, the preposition generated significant debate.

The resulting discussion bifurcated as per the previous discussion into model house keeping difficulties and philosophical modelling strategy discussions. The philosophical discussion was triggered by the notion of how to codify the ‘value’ of land, water, natural and cultural assets. This is a longstanding limitation of Integrated Assessment Models for the economic value of intangible assets, especially assets that can have a huge emotional quotient are problematic to model. Modelers have tried to escape this conundrum by utilizing a range of weights for which assets such as land, water, biodiversity and cultural regions may be categorized such that programmatic constraints may be built that forces computer models to push solutions towards brownfields rather than regions of biodiversity, as an example. However, this approach albeit widely utilized is problematic for it still places a form of value upon a given asset. And as such the computer models will still exploit the asset if the constraint and optimization engines are forced into an expensive choice if no other solution is available. Therefore, continued use of weights as a proxy for economic value was cautioned albeit a common approach.

To escape the tyranny of weighting schemes that cannot escape an emotional quotient the emergence of hybrid human directed computable scenarios were illuminated that has been utilized in a few early test studies and working groups, notably Uganda and New Zealand [69, 70]. Specifically, integrated assessment models with nexus attributes have been utilized to explore energy development pathways for climate mitigation strategies but these tools have been employed/embedded within a citizen assembly of stakeholders. As development pathways are explored real time interaction with a collective of stakeholders/policy makers allows unacceptable computer optimization choices to be precluded. This dual hybrid approach was particularly efficacious in New Zealand where the guidance to the human stakeholders was fashioned by rules and constraints that were enshrined in protective environmental and cultural legislation. The approach was deemed to be effective because it allowed all stakeholders to become active policy pre-development contributors rather than late-stage post-policy re-activists trying to oppose a specific development.

Provision and acuteness of the provisioned data sets for inclusion in the model when including the nexus (3 or 5) frameworks was flagged as a highly problematic requirement. In general, widescale data sets do not exist and construction of such data sets was encouraged to be drawn only from those institutional agencies that have a long-standing record and mandate to refresh and maintaining data sets on an enduring basis. Too many models currently utilize data sets with inferenced or non-referential data proxies and reasonable guesstimates. This undermines trustworthiness and utility of any given proposed policy that is presented as an outcome of a specific investigation. Furthermore, consistency of data representation across spatial scales was also deemed to be critical. Fundamentally sparse data is a problematic and enduring issue.

5.2.1. Data complexity and accuracy

Expansion of coupled models to explore policy scenarios that include variants of the nexus constructs for land and water and indeed the UN 17 SDGs in addition to energy economies and engineering requires the collation of heterogeneous data sets. That is,
data sets from many disparate sources. This immediately raises concerns of compatibility, i.e. assurance of simple units and metrics being compliant and harmonious across the input data. Furthermore, the providence of the contributing data set is also of concern, basic issues such as accuracy are obvious. But legal access to data, the licensing and access to private and government data sets, compliance and attribution tracking all impose the need for integrated data asset management tools.

Concerns for full data coverage were raised with the potential need for data extrapolation exercises to be invoked to ‘fill’ the gaps between disparate data sets. How can missing or unreliable data be identified and/or be fixed? Therefore, the recommendation to avoid highly integrated coupled models was strongly supported but the notion of systematic utilization of existing models to be soft coupled dual expert driven such that wider policy scenarios could be explored was supported.

5.2.2. Intangible ‘emotional’ assets
Energy-Economy and Energy System Engineering models have the luxury of dealing with mathematical tractable variables, constraints and costs. Once the inclusion of land and water is included into the modeling environment this rigorous foundation is undermined because in many situations there is a huge emotional quotient associated with the definition of the resource. This observation becomes increasingly problematic when regions of biodiversity (natural security) and culturally important areas (cultural security) are attempted to be included into the modeling scenarios. Further expansion to include the United Nations 17 SDGs becomes difficult for many are not tangibly codified as measurable variables or constraint.

Economists have often attempted to place economic value upon ecosystem services, as a means to quantify the trade-offs associated with impactful resource development. This is exacerbated when it is realized that SDG’s are global in scope but often contradictory within specific geographic regions where the emotional ‘quotient of land, water, natural and cultural security’ is valued very differently. Thus, a homogenous representation of these assets over a wider geography is not readily adopted. Furthermore, it was strongly argued that trying to sidestep the notion of value by utilizing constraints that protect or weight assets as more or less important is simply a semantic exercise. Ultimately a value is still being placed upon an asset and when employing models that exploit constraint-based optimization if a resource is sufficiently scarce but needed the optimization engine will exploit the needed resource, albeit at a high cost. This fundamental limitation catalysed a philosophical discussion that again supports the dual expert human guided modeling paradigm.

5.2.3. Invoking dual expert human directed modeling environments
To escape the impediments of modeling ‘emotional quotients’ the notion of equity, justice and cultural recognition came to the fore in the discussion. This re-introduced the notion of the dual expert human guided modelling paradigm but at a larger scale of human inclusion. Specifically, references were drawn from New Zealand and Ugandan exercises where land, water, biodiversity and cultural rights have been enshrined in law and have associated guardian stakeholder groups [69, 70]. As policy scenarios are explored for developments that advance SDG’s and energy engineering responses to climate change, the optimization and/or simulation models are directed/guided with stakeholders debating and conceding or blocking in a parallel yet coupled activity. This was deemed as a tenet of an advanced democratic society, the approach is effective because it allows all stakeholders to become active policy contributors rather than late-stage post-policy re-activists trying to oppose a specific development. Thus, the notion of citizen assemblies being utilized to guide and draft policy development in a co-evaluation process with computer models was deemed as an important consideration. Therefore, natural justice is fundamentally incorporated into the policy development process for the stakeholders are empowered through legislation and/or constitutional rights. It is an approach that allows the escape from the tyranny of attempting to cost, weight or value tangible assets that are valued on an emotional basis to be achieved.

5.2.4. Inclusion of socio-technical modelling tools
Finally, system dynamics was flagged as a key issue when modeling nexus systems. The concern is that when attempting to model the interactions between the major sectors (energy, land, water, natural and cultural security) the unintended (intrinsically modeled) feedback loops invoked by pressures and drivers upon one sector by exploitation of another sector need to be very carefully considered. This is of concern when soft-coupled models are directed or guided by human experts because the expanded complexity of the system clouds true understanding of the behaviour of the model—i.e. the response to given stimuli or resource exploitation may have unintended modelling consequences that are simply artifacts of the construction of the modelling environment. These artifacts are hidden by the complexity of the model and as such lead to policies that have unforeseen flaws embedded.

These concerns echo the previous sections’ recommendations where less complex models that are well understood can be coupled to explore a wider range of scenarios more reliably than scenarios where highly complex, tightly integrated coupled models
Table 3. Modelling evaluation framework.

| Criteria | Description | Rating scale |
|----------|-------------|--------------|
| (a) Open source | Model code and documentation are open source and freely available to enable auditing and transparency. | 4—fully openly licensed code  
2—code is available but not openly licensed  
0—code is not available for audit |
| (b) Open data | Model data is freely and openly licensed for reuse to enable follow-on analysis and transparency. | 4—fully openly licensed data  
2—data is available but not openly licensed  
0—data is not available for audit |
| (c) Data provision | The provision of data is clear and well documented, such that model assumptions can be updated. | 2—fully met  
1—party met  
0—not met |
| (d) Temporal resolution | The temporal resolution should be high enough to represent the features of interest. | 2—fully met  
1—party met  
0—not met |
| (e) Spatial resolution | The spatial resolution should be high enough to represent the features of interest. | 2—fully met  
1—party met  
0—not met |
| (f) Stakeholder involvement | Stakeholders and lead agencies are involved from the start to allow for better understanding of the limitations and inform correct use of the results. | 2—fully met  
1—party met  
0—not met |
| (g) Standardization and synchronization | Clear processes for data handling and shareability, templates and standard structures for ease of re-use. | 2—fully met  
1—party met  
0—not met |
| (h) Documentation | Code documented by software experts, full documentation of assumptions, scenarios, data sources, etc. | 2—fully met  
1—party met  
0—not met |
| (i) Addressing nexus interactions | Water: WF, WC, WL, WE  
Energy: EW, EC, EE, EL  
Land use: LE, LC, LW, LF  
Climate: CL, CE, CW, CF  
Food: FC, FL, FE, FW  
This category can be expanded with additional interactions as needed. For example, Niet et al [65] argue that economic well being, health and ecological diversity should be included in nexus analyses. These interactions with water, energy, land, climate and food could be included here as well. | One point per interaction effectively incorporated into the model. 0.5 for any partial interactions |

are created that are hard to audit and confirm trustworthiness. The expansion of modelling complexity to include the nexus gives cause for concern as model complexity will increase considerably if reasonable nexus representation is to be achieved.

Appendix D: Expert elicitation focus group summary notes provides the summary notes from the focus groups with additional details and participant thoughts and ideas.

6. Modelling evaluation framework

Based on the feedback from the experts in the focus groups, as well as the literature review, the focus of modelling efforts should be on transparent analysis covering different aspects of the nexus and increasing model complexity only where needed to address specific research questions. This brings us to a framework for evaluating modelling projects which goes beyond just combined modelling and is applicable to any nexus modelling activity. Table 3 shows the components of the modelling evaluation framework proposed in this paper.

The framework in table 3 provides a simple way of comparing models and their representation of the nexus and their usefulness to open and transparent analysis, with higher scores indicating higher levels of nexus representation, higher levels of openness and better standardization and documentation.

Similar to the work by Khan et al [53] who they identify 15 features of integrated modelling, we identify a set of nine features of nexus modelling that are important for effective analysis. The 15 items Khan et al identify are included in the nine below with, for example, their item 15 (synchronized future scenarios) being incorporated into our number 7. Koppelaar et al [71] and Zhang et al [72] similarly provide reviews of the purposes and capabilities of different nexus modelling approaches, but neither work provides an evaluation framework that can be applied to comparing modelling efforts on a numerical scale. The framework we present can be applied to any nexus modelling activity to get a sense
of how well that activity represents the nexus and how well it addresses the additional aspects identified in our expert elicitation focus groups, namely open modelling and standardized data processing and documentation. Although we expect that the numerical grading of the framework will only be applied occasionally, the identified aspects and their descriptions should be used by modellers to evaluate their modelling approach and move towards better/best practices.

7. Conclusion

This work provides a framework for evaluating nexus modelling activities both internationally and within Canada. Starting with the potential for combined modelling as an approach to addressing nexus challenges, we performed a detailed literature review and convened a series of expert elicitation focus groups to determine best practices for combined and integrated modelling of nexus challenges.

The main findings from the literature review indicate that there are significant gaps in the representation of the nexus in models in the literature. Specifically, only one or two modelling approaches include multiple aspects of the nexus in any systematic way. The literature review also identified that interactions in both directions are important, for example, it is not sufficient to include just water impacts on the energy system (through energy for water pumping, for example), but energy impacts on water through cooling water needs and water for hydro dams are also important. Nexus analysis must be bi-directional, with impacts in both directions included into the analysis.

The expert elicitation focus groups identified that open-source models and openly licensed data, as well as clear documentation, data providence and stakeholder involvement are critical for modelling success. These provide transparency and the ability to audit and re-do analysis, as well as the ability to create and analyse scenarios that clearly address the questions and concerns of the stakeholders. Without open-source modeling and openly licensed data any analysis performed is, by definition, unable to be repeated nor audited. This aspect of integrated modelling is not well discussed in the literature but is an important aspect that came out in the expert elicitation focus groups.

Combining these two sources, we created a framework of nine components to consider when implementing integrated modeling activities to address nexus challenges. From the expert elicitation focus groups, we identified open-source modelling, openly licensed data, data providence, stakeholder involvement and standardization as critical components of any integrated modelling activity. The literature review added considerations of temporal and spatial resolution, synchronization of scenarios, documentation and addressing bi-directional aspects of nexus interactions.

This framework allows modellers to rank/evaluate how well a given approach addresses nexus challenges. We hope this will help guide both future modelling activities and aid the modelling community in addressing these challenges in a robust and constructive manner, with clarity on what aspects of the nexus challenge to focus their efforts at addressing.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

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Appendix A. Overview of existing models

Table A4. Main existing models in each level of energy system and their main sectoral focus.

| Model class                  | Sample of modelling tool                                                                 | Modelling paradigm                                                                 | Typical application/analysis                                                                 | Strength                                                                 | Limitation                                                                 | Sectoral focus                                                                 | More info | Note                                                                 |
|------------------------------|-------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------|---------------------------------------------------------------------|
| Energy-economy models        | PRIMES (price-induced market equilibrium system) [35, 40, 73]                             | Partial equilibrium model                                                          | • Detailed energy system projection                                                           | • The distinctive feature of PRIMES is its hybrid equilibrium nature of the model, it lacks closed-loop energy-economy equilibrium analysis. This means the equilibrium established between supply and demand in each scenario cannot send a feedback to the rest of the economy [73] | Due to its partial equilibrium nature of the model, it lacks closed-loop energy-economy equilibrium analysis. This means the equilibrium established between supply and demand in each scenario cannot send a feedback to the rest of the economy [73] | Economy-engineering Electricity and gas trade within EU international market Behavioural model that captures: Demand Supply Pollution abatement technologies related to energy use | [32]      | Similar model in capability: NEMS used by US-EIA/DOE [35]—PRIMES developed based one the needs of European energy system while NEMS is based on USA energy system |
|                              | PRIMES (price-induced market equilibrium system) [35, 40, 73]                             | Hybrid model, embedding technologies in economic decisions [73]                    | • Impact assessment for energy and environment policies                                      | • Market orientation                                                       | Only scenario projections not forecasting                                    |                                                                  |           |                                                                     |
|                              | PRIMES (price-induced market equilibrium system) [35, 40, 73]                             | Designed as modularity (separate modules for each S&D&P sector) [35], price-induced market equilibrium system [40] | • Energy-economy-environment policy analysis in linked to GEM-E3 (macroeconomic/sectoral activity model) and GAINS (air pollution interactions and synergies) models | • Focus on demand side behaviours [73]                                    | Lack of high spatial resolutions below country level                        |                                                                  |           |                                                                     |
|                              | PRIMES (price-induced market equilibrium system) [35, 40, 73]                             | PRIMES (price-induced market equilibrium system) [35, 40, 73]                      | • Energy-economy-environment policy analysis in linked to GEM-E3 (macroeconomic/sectoral activity model) and GAINS (air pollution interactions and synergies) models | • Focus on demand side behaviours [73]                                    | Lack of high operational/ engineering resolution and representation, so cannot deliver short-term engineering analysis [35] |                                                                  |           |                                                                     |
Table A4. (Continued.)

| Model class | Sample of modelling tool | Modelling paradigm | Typical application/analysis | Strength | Limitation | Sectoral focus | More info | Note |
|-------------|--------------------------|-------------------|----------------------------|----------|------------|---------------|-----------|------|
| GCAM [34]   | Partial equilibrium model (price-induced model system) | Defined by its developer as a global integrated assessment model (IAM)P1F [34] | • Understanding the physical and economic details of human and physical Earth system interactions. | • Captures the complex interactions between five systems: energy, water, agriculture and land use, the economy, and the climate [34] (mostly exogenously) | • Lack of high operational/engineering resolution, so cannot deliver short-term engineering analysis | • Macro-economy and energy system: 32 geo-political regions at the global scale | [74] |
|             |                          |                   | • Explore the role of uncertainty in shaping events | | | | |
|             |                          |                   | • Simulation of future carbon emissions | | | | |
| CIMS [33]   | Hybrid top-down bottom-up model; an integrated, energy-economy partial equilibrium model | Simulation of the interaction between energy S&D with the macro-economic performance of key sectors of the economy, (including trade effects) | • It is able to model consumers' choice of new technologies | | | | |
|             |                          |                   | • Reflects some of uncertainties and imperfect information in decision making | | | | |
|             |                          |                   | • Cannot do optimization | | | | |
|             |                          |                   | • Lacks high operational and engineering resolution, so cannot deliver short-term engineering analysis | | | | |
|             |                          |                   | • Currently lack of spatial extent | | | | |
|             |                          |                   | • Difficult to understand due to archaic language [33] | | | | |
|             |                          |                   | | | | | |
| Model class                                      | Sample of modelling tool                                   | Modelling paradigm                                                    | Typical application/analysis                                                                 | Strength                                                                                                                                                                                                 | Limitation                                                                                                                                                                                                 | Sectoral focus                                                                                     | More info                                                                                       | Note                                                                                                      |
|-----------------------------------------------|------------------------------------------------------------|-----------------------------------------------------------------------|--------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| NEMS (National Energy Modelling System)       | • Partial equilibrium                                      | Projection and simulation of the energy, economic, environmental, and security impacts of alternative energy policies through scenarios | It includes behavioural and technological choices criteria                                                                                   | • Lack of high operational/engineering resolution                                                                                                                                       | • Electricity and heat [40]                                                                                                                                   | • National energy policies                                                                                   |                                                                                               | Similar model in capability: PRIMES [35] but designed for the United States                                                                         |
|                                               | • Energy-economy modeling system                           |                                                                                                                                  |                                                                                              | • Lack of representing technologies with current abroad small market potential [76]                                                                                                                   | • Power sector                                                                                                                                                                                | • Residential and commercial building sectors                                                   |                                                                                               |                                                                                                                                                |
|                                               | • Defined by its developer as integrated assessment model2P |                                                                                                                                  |                                                                                              | • Lack of spatial resolution for state-level analysis and poor global application [36]                                                                                                             | • Transportation sector                                                                                                                                                                           | • Oil and gas recovery                                                                                |                                                                                               |                                                                                                                                                |
|                                               |                                                            |                                                                                                                                  |                                                                                              |                                                                                                                                                                                                          | • Petroleum product and their substitutes [76]                                                                                                                                   |                                                                                                                                                     |                                                                                               |                                                                                                                                                |
| Capacity expansion models                     | OseMOSYS (the open source energy modeling system)          | • Bottom-up linear programming (LP)                                                                                              | Helps investment decision in new energy capacity expansions by estimating the lowest net present value (NPV) cost of a specific energy system to meet the demand for both energy services and energy [15] | • Overall, it is a simple, open, flexible and transparent model that can replicates the results of many popular and commercial tools, such as MARKAL (adjustment may be needed) | • As a LP model, it does not take the effect of uncertainty and time into consideration                                                                                                      | Core model represents the power system, but structure allows extensions of the model to other sectors | [78]                                                                                           | Welsch et al [78] showed that by adding detailed operational constrains to OseMOSYS (without increasing the temporal resolution), the model can almost reproduce the results of combined TIMES/PLEXUS (high temporal resolution) |
|                                               | • System optimization model                                |                                                                                                                                  |                                                                                              | • Designed as a research/training model                                                                                                                                                    | • As an LP model, many parameters are assumed to be constant which is far from reality                                                                                                    |                                                                                                                                                     |                                                                                               |                                                                                                                                                |
|                                               |                                                            |                                                                                                                                  |                                                                                              | • It allows a test-bed for new energy model developments [15]                                                                                                                                     | • Limited to a single object at the time, while in reality situations are often multi-objective interactions                                                                                   |                                                                                                                                                     |                                                                                               |                                                                                                                                                |
|                                               |                                                            |                                                                                                                                  |                                                                                              | • Since it is an open-source model, it can be easily updated and modified to suit the needs of a particular analysis and modeler [15]                                                                 |                                                                                                                                                                                             |                                                                                                                                                     |                                                                                               |                                                                                                                                                |

(Continued.)
| Model class                          | Sample of modelling tool | Modelling paradigm | Typical application/analysis                                                                 | Strength                                                                                                                                                                                                 | Limitation                                                                                                                                                                                                 | Sectoral focus                                                                                                                                                                                                 | More info | Note |
|-------------------------------------|--------------------------|--------------------|-----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|------|
| MARKAL (market and allocation) [79] | • Linear optimisation    | • Partial equilibrium [40] | • Least-cost energy systems planning considering policies, taxes, subsidies  
• Project impacts of system on future emissions  
• Compare scenarios with and without regional cooperation [80] | • Applies from global scale to isolated local energy systems [40] | • Input data that completely describes the system can be challenging to obtain [81]  
• Extensive training and experience required [82] | • Energy system planning and system costs  
• Costs and system impact of policy, environmental restrictions, taxes, subsidies | [83] | |
| MESSAGE (model of energy supply systems and their general environmental impact) | • Systems engineering optimization model (all GHGs, all energy sectors, water) [84] | | • Energy policy analysis and system planning for the medium to long-term horizon  
• Development of technology strategies and related investment portfolios to meet policy objectives’ [37] | • Represents all aspects of the energy system from extraction/imports/exports to end-use services [85]  
• Has user-controlled time horizon for analysis [82]  
• Flexible [82] | • ‘Difficult troubleshooting, low clarity of user manual, very tricky data input, level of difficulty in running model is higher’ [82]  
• Inputs for the model are detailed on the supply side but the demand inputs are more aggregated [86]  
• As a LP model, it does not take into consideration the effect of uncertainty and time  
• As an LP model, many parameters assume to be constant which is far from reality and | • Optimal energy system planning at the regional and national level  
• Energy demand projections (MAED) [37], note that Baseline energy service demands are provided exogenously to MESSAGE, however some endogenous adjustments can be done based on energy prices by linking MESSAGE and MACRO [87] | [88] | |

(Continued.)
| Model class                  | Sample of modelling tool | Modelling paradigm                                                                 | Typical application/analysis                                                                                                                                  | Strength                                                                                                                                                                                                                   | Limitation                                                                                                                                                                                                                       | Sectoral focus                                                                                                                                                                                                                     | More info          | Note |
|-----------------------------|--------------------------|------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|------|
| Power system models         | PLEXOS                   | • Market simulation software [19]                                                   | • Deterministic and stochastic optimization methodology (mixed-integer, linear and non-linear) [40]       | • Pre-calibrated by the developer for many situations                                                                                                                                                                           | Expensive for non-commercial applications [19]                                                                                                                                                                           | Electricity system planning and operation can co-optimize: • Thermal • Hydro • Energy/reserve/fuel markets • Contracts                                                                                                                                 |                   |      |
|                             |                          | • Electricity market modeling and planning                                          |                                                                                                         |                                                                                                                                                                                                                           |                                                                                                                                                                                                                        |                                                                                                                                                                                                                                |                   |      |
|                             |                          |                                                                                    | • Minimization of overall system operational cost • Capacity expansion and investment planning • Market analysis or design • Price forecasting and risk analysis • Portfolio optimisation and valuation • Transmission and ancillary services analysis • Renewable integration analysis and optimisation • Integrated electric and gas system market modelling • ‘Co-optimisation of other commodities (water, heat etc)’ [89] |                                                                                                                                                                                                                           |                                                                                                                                                                                                                        |                                                                                                                                                                                                                                |                   |      |
|                             |                          |                                                                                    |                                                                                                         |                                                                                                                                                                                                                           |                                                                                                                                                                                                                        |                                                                                                                                                                                                                                |                   |      |

(Continued.)
### Table A4. (Continued.)

| Model class | Sample of modelling tool | Modelling paradigm | Typical application/analysis | Strength | Limitation | Sectoral focus | More info |
|-------------|--------------------------|-------------------|----------------------------|----------|------------|---------------|-----------|
|             |                          |                   |                             |          |            | Power distribution | [92]       |
|             |                          |                   |                             |          |            | Power transmission |           |
|             |                          |                   |                             |          |            | Industrial system |           |
|             |                          |                   |                             |          |            | Power generation |           |
|             |                          |                   |                             |          |            | Distributed generation |           |
|             |                          |                   |                             |          |            | Renewable integration |           |

**PowerFactory**

Network power management model

- Analysing generation
- Transmission, distribution
- The integration of renewable generation into distribution, transmission and industrial networks

Generic strengths of power system models:
- Rich in system operational details
- Representing individual plant and unit commitment and system dispatch at high temporal and spatial resolutions

Generic limitations of power system models are:
- Limited in projecting the power system evolution over time

**GridCal**

Research oriented power systems software

‘Design and implementation of electrical calculation software (power flow, short circuit, voltage collapse, stochastic calculation and network collapse)’ [39]

- Not specified in available document
- Generic strengths of power system models:
- Rich in system operational details representing individual plant and unit commitment and system dispatch at high temporal and spatial resolutions

- Not specified in available document
- Generic limitations of power system models are:
- Limited in projecting the power system evolution over time

*Power sector*
| Model class | Sample of modelling tool | Modelling paradigm | Typical application/analysis | Strength | Limitation | Sectoral focus | More info | Note |
|-------------|--------------------------|--------------------|-----------------------------|----------|------------|----------------|-----------|------|
| PyPSA (Python for power system analysis) | • Simulation and optimization of electrical power systems | "Investment and operation decision support, power system analysis tool (power flow and contingency analysis)" | • Not specified in available document Generic strengths of power system models: • Rich in system operational details representing individual plant and unite commitment and system dispatch at high temporal and spatial resolutions | • Not specified in available document Generic limitations of power system models are: • Limited in projecting the power system evolution over time | Power sector | | |

\(^a\) S&D: supply and demand.

\(^b\) There is a disagreement on the definition of IAM as one may argue that partial equilibrium models lack a close-loop representation of the whole economy.
### Appendix B. Temporal and spatial resolution

Table B5. Temporal and spatial resolutions of modelling approaches and their accessibility.

| Models class     | Sample of modelling tools and approaches | Temporal resolutions | Current temporal extent | Spatial resolutions | Current spatial extent | Open source          | Model2F a | Solver                        |
|------------------|-----------------------------------------|----------------------|-------------------------|---------------------|------------------------|----------------------|-----------|--------------------------------|
| Energy-economy models (EE) | PRIMES [35, 40, 73] | Low: 5 years’ time-step | 2000–2050 | Medium to long-term analyses that span over decades | Europe: country-by-country in European context | Not specified in available documents | Not specified in available documents |
|                  | GCAM [93]                      | Low: 5 years’ time-step | Runs through 2095 | ‘GCAM has been designed to allow for a “telescoping capability” to allow greater resolution in sectors or regions’ | 32 geo-political regions at the global scale | Yes, with additional open source software [94] | Not specified in available documents |
|                  | CIMS                         | Low: 5 years’ time-step | Not specified in available documents | Seven regions: BC, AB, SK, MB, ON, QC, aggregation of Atlantic Provinces [33], Canada, China | Not specified in available documents | Commercial | Commercial |

(Continued.)
| Models class                | Sample of modelling tools and approaches | Temporal resolutions | Current temporal extent | Spatial resolutions | Current spatial extent | Open source                                                                                                      |
|----------------------------|------------------------------------------|----------------------|-------------------------|---------------------|------------------------|-----------------------------------------------------------------------------------------------------------------|
| NEMS [95]                  | Solver                                   | Low: yearly (some component seasonal) [40] | 2050 [40]               | Long-term           | Design for USA context (regional and national)                                                                |
|                            |                                          |                      |                         |                     |                        | • Yes, the source code                                                                                         |
|                            |                                          |                      |                         |                     |                        | • 'Because EIA, as the NEMS developer, is a federal entity, most of what constitutes NEMS is in the public domain (and no licenses are required to access or use it). However, NEMS does contain some proprietary components that are outside the public domain' [36] |

**Capacity expansion models (CE)**

| MARKAL                     | Multiple years of fixed length—(user can define time-slices within a year) [40] | Long-term: multiple years, usually 40–50 | Local and regional | In 40 countries | Commercial                                                                                                      |
|                           |                                           |                                     |                      |                     | Only source code, needs additional commercial software [94]                                               |
| OSeMOSYS                   | Medium: Can be defined by user (usually seasonal, or intra-annual) [40]          | User-defined [40]                   | Community to continental [40] | OSeMOSYS has been applied in at least 30+ countries   | Open source                                                                                                      |
| MESSAGE                    | Multiple years (user-defined) [40] usually 5–10 year time-step [86]              | Medium (1–5 years) to long-term (1–40 years with maximum of 120 years) [86] | National and global | Global and 11 nations [40] | • Available upon request [40] for academic purposes                                                             |
|                            |                                           |                                     |                      |                     | • Note: It comes in different variation, for instance, MESSAGEix is open source (but the solver is not) [96] |

(Continued.)
| Models class | Sample of modelling tools and approaches | Temporal resolutions | Current temporal extent | Spatial resolutions | Current spatial extent | Open source | Model2F \(^a\) | Solver |
|--------------|------------------------------------------|----------------------|-------------------------|-------------------|-----------------------|-------------|----------------|--------|
| Power system models (PS) | PLEXOS | Short to long-term: can be defined by user up to 1 min (usually hourly) [40] | User-defined: from long-term (1–40 years) to medium-term (1–5 years) to short-term (less than 1 year) [40, 90] | Very diverse: from single project/technology to local, regional, national or global scales | Varies | Not specified in available documents | Not specified in available documents |
| PowerFactory [38] | Not specified in available documents [40] | Not specified in available documents | Not specified in available documents | Not specified in available documents | | | | |
| GridCal | Not specified in available documents | Not specified in available documents | Not specified in available documents | Not specified in available documents | | | | |
| PyPSA (Python for Power System Analysis) | Hourly | One year | National | Not specified in available documents | Yes, with additional open source software [94] | | | |

\(^a\) Note that being an open source software varies from being free to access.
### Appendix C. Overview of existing combined modelling efforts

| Example of combined modelling approaches | Objectives of using the combined modelling techniques | Flow of information | Note on main findings and strengths | Note on challenges and limitations | Reference publication |
|------------------------------------------|------------------------------------------------------|---------------------|-------------------------------------|----------------------------------|---------------------|
| ReEDS (CE) + PLEXOS (PS) (framework)     | To enable power system models to incorporate the long-term expansion energy projections | One-way coupling: ReEDS → PLEXOS  
- The main output information transferred from ReEDS to PLEXOS: location, type, and capacity of new and retired generators | Finding: coupling helps capacity expansion models to better represent the variable renewables in their aggregated-form of the unit commitment and dispatch system | Challenge: PLEXOS, similar to other power system models, is designed to function on a static database, so it does not allow including new generators inputs from ReEDS | Diakov et al [60] |
| Irish TIMES (CE) + PLEXOS (PS)           | To examine the suitability of features such as the system reliability and flexibility, renewable energy generation curtailments, and CO\textsubscript{2} emissions reduction calculated by Irish TIMES | One-way coupling: TIMES → PLEXOS  
- The main output information transferred from TIMES to PLEXOS: electricity generation portfolio, fuel prices, and carbon prices | Finding: the work showed that in the absence of the detailed technical constraints of the power system model, there is an inconsistency in assessing flexibility and calculation of the CO\textsubscript{2} Remissions reductions | Limitation: the assumption that a future variable renewable energy supply portfolio can be represented by the historical data | Deane et al [7] |

(Continued.)
### Table C6. (Continued.)

| Example of combined modelling approaches | Objectives of using the combined modelling techniques | Flow of information | Note on main findings and strengths | Note on challenges and limitations | Reference publication |
|----------------------------------------|-----------------------------------------------------|---------------------|------------------------------------|-----------------------------------|----------------------|
| POLES (energy-economy model) + EUCAD (PS) | To investigate the effect of low operational resolution and fix assumption on the availability of renewable energies (wind in this case) on operation costs, system flexibility, and energy expansion investments | Two-way coupling: POLES ↔ EUCAD  
- The main output information transferred from POLES: load, variable costs, installed production, storage and interconnection capacities, energy available for dispatching  
- The main output information transferred from EUCAD: the generator-by-generator unit commitment and dispatch analysis and other production curtailments | • Strength: one of the unique aspects of this work is the two-way coupling methodology to exchange information back-and-forth between models  
• Finding: reflects the importance of having operational details in creating a reliable and realistic projection of technical and economic challenges in the integration of a high share of variable renewable energy sources in the power system | Després [62] |
| Example of combined modelling approaches | Objectives of using the combined modelling techniques | Flow of information | Note on main findings and strengths | Note on challenges and limitations | Reference publication |
|-----------------------------------------|-----------------------------------------------------|---------------------|------------------------------------|-----------------------------------|------------------------|
| PRIMES (energy-economy model) + PLEXOS (PS) | To investigate the curtailments of having high renewable energy generations in the system, levels of interconnector congestions, and wholesale electricity prices | One-way coupling: PRIMES → PLEXOS • The main output information transferred from PRIMES: installed generation capacity by members, annual electricity demand by members, fixed fuel price, generator efficiency by members, annual capacity factors | • Finding: captured elements that are not represented otherwise in the long-term energy system decisions such as the potential share of variable renewable power • Finding: PRIMES demonstrated overly optimistic results about the flexibility of the grid with high RE penetration | • Challenge: the main challenge was the disaggregation of installed generation capacities developed for each Member State in PRIMES to reflect geographical and operational details required in the power system model | Collins *et al* [32] |
Appendix D. Expert elicitation focus group summary notes

This appendix provides the detailed notes summarized, by topic, from the expert elicitation focus groups.

**Best practices/guidelines for fidelity**

- Open source models and transparency
  * Having open access, and something free of cost is vital
- Collaboration: no one person knows everything
  * Collaboration between experts in different fields/from different backgrounds, or those using different models
  * Stand-alone models are great, but divides between different sectors must be removed
  * Having interdisciplinary teams with more understanding of different sectors/areas are more important than coupling models
  * CONS: collaboration costs a lot of time

Different IT skills, interfaces between different models and maybe languages
Interpersonal problems can be caused from lack of technical details.

**Standardization**

- Routines, interfaces, and automated processes (avoiding human error)
- Ways to standardize: scripted workflows, semantics for data, agreeing on metrics
- Allows others to use the models
- Allows contributions to be orderly.

**Documentation**

- Keep track of what’s going on, and why
- Smoother process of communication starts at very beginning (avoid reverse engineering)
- Avoid having to re-do work
- Researchers are not always best at this

Valuable to have teams of data or software engineering experts
Avoiding undocumented code
Building complex models requires organization

- Document verification of scenarios

Know that they work, and how they work
Better to have well-documented bad data than poorly documented good data.

**Model input and output, and synchronization**

- When combining models, important to understand input and output and finding similarities
- Synchronize variable names and output formats
- Use a master template from the very beginning (spreadsheet with parameters and output reporting format)

Project can be very time consuming without this
Define what each variable means (units, what is being measured)

- When combining models, having an automated workflow is important

Reproducibility—fixed and documented, automated, reproducible, pre-defined variables (e.g. GDP in all models are the same).

**Matching metrics**

- Example: LCOEs

Can be bad for decision making, but policy makers trust it
Worked for conventional technologies, but not anymore

- Current metrics do not match the increased complexity of the system

More/new tools and metrics are needed
Factoring in new things to the old metrics may not work (logical issue, current metrics based under a different power regime)

- Challenge is to incorporate different pieces into the model in an effective way. Dealing with temporal challenges (e.g. 50 year model, 10 min variability with wind)

A way to do this is to run a long haul model that calls out to much finer grained annual model from time to time
This requires quite skilled model coupling, particularly if across time optimization is used.

**Accuracy**

- Combining models can cause a lack of accuracy

Uncertainties would propagate/expand (not narrow down)
Hard to meet a certain acceptable level of accuracy

- Experience: accurate model with hourly time slices

Model became unnecessarily complex
Not cross checking leads to not optimal solutions with compressed time slices. Interesting idea: Have time slices not explicitly used but just for the model to gain accuracy

- Large scale system models

Start large scale, then think about using it to derive helpful messages
Understanding the behaviour of large scale computer models
In order to do any sort of uncertainty treatments, you typically need more runs. Scenarios
By trying to get more detail for accuracy, what exists can be degraded
As you add features, complexity rises, statistical testing is fuzzier, and it is counterintuitive to what you hoped
Making a decision vs higher accuracy
* Decision support mechanism is more important
* Exactly how things will pan out might be very unclear, but what needs to be done might not be a particularly difficult decision
* What looks the most appropriate decision can be very insensitive for different perspectives
* What approaches can organizations in the ‘real world’ outside of research bring
* Trying different alternatives, try different things to support decisions

Work on different angles/professions, different amounts of appropriate analysis to do
Long term goal to translate different approaches for broad spectrum of analysts
Sometimes approaches that are optimal in a model world are not even implementable.

Assumptions
* Having one combined model: underlying assumptions are similar/consistent/without contradictions
* Having separate models/model coupling: friction in harmonizing data and assumptions.

Comparing models
* Healthy to talk through semantics and assumptions made
* Whether or not the scenarios are the same.

Soft links (example with electricity, transport and heating and cooling)
* PROS
  * Model done quickly to support the government, insight for policy makers
  * Combining models provided more information for sections that other models did not cover
* CONS
  * Discrepancy between models, policymakers go with the one they trust more

Discrepancies caused by lack of detail in one model (not lack of transparency, but just the nature of how model was built)
No changes of models was made to address discrepancies.

IAMs and integrated assessment tools
* Fundamental assumptions of IAMs are different than other models
* Trend: Mega models -> creating big models that are easily customizable/downsize-able
* Different paradigms of describing economy and energy transition
* Trying to build a unified tool that helps in translating some of these discrepancies
* Fidelity is a complicated problem. Would use a bottom-up approach
* Look at policy gaps and how it can be closed.

Complexity and fidelity
* The model itself vs the model as a tool for exploring a problem space
* Fidelity is a measure of trustworthiness or accessibility
  * Is the model fit for purpose and able to do what it is supposed to do
  * Being careful about how structure/nature of model selected is driving the outcome you are going to see
  * Open source vs not
* If a model is complex, it can lead to overconfidence of the system
  * Trade-offs between a model that is complex enough to capture system, but the more complex a model, the harder it is to understand what it is doing
  * The benefit of a set of 5 models (each focused on different things) instead of 1 complex model:

The complexity of separate models come from the interactions between models, so they are easier to understand individually.

Purpose of modelling
* Fidelity
  * Measure of trustability and accessibility
  * Model captures the important dynamics of the system with appropriate input data to give a sense of realistic outputs
  * Fit for purpose
* Getting insights and not just numbers
  * Currently, a lot of focus on model output in terms of numbers
  * Consider the position of ‘the numbers can be interesting and important, but that’s maybe not the most interesting part of modelling’
  * Moving away from single number outputs and towards model output envelopes

Think about preferences of decision makers, allow for model generated alternatives
* Think of models as (future) exploration and communication devices, conversation tools
* Pay less attention to specific outputs (and specific outputs will not necessarily be completely accurate)
* Understanding what the model can tell you, and how to use it
* It is more interesting when you take set of outputs to compare in relation to each other
‘The more you dig into models, the more you realize they deviate from reality’

- Level knowledge one has:
  - Might have limited knowledge but have to make decisions in that field
  - Overwhelming uncertainty, but important to work out what one actually does know, and how to structure thinking so you begin to get somewhere
  - Sometimes you can reduce key questions into a manageable number of factors
  - One of the points is recognizing the limitation of what is knowable and sometimes decision making in reality (not uncertainty).

- Describing results
  - Include confidence in statement
  - Carefully communicating results to public/policy makers.

Decision makers
- Different stages to include them in the process?
  - Decision makers helping define problem space vs modeller chooses and presents the results
  - Important to describe to decision makers in a succinct and intuitive way how the model functions
  - Be clear about what the model cannot do
  - If decision makers want to know more, can the model be more complex? Can it be tied to another model?
  - Ex. OSeMOSYS does not tell what happens to jobs
  - Decision makers make choices with long life-times and path dependencies
  - Be explicit about uncertainties, and understand uncertainties vs sensitivities.

Lead agencies
- Accurate data: engage ministries in charge of different aspects.

Best practices/guidelines for best representation of the SDGs/nexus
- Data sets
  - Datasets for nexus models will be much more heterogeneous than other modelling, they create more complexity/problems.
  - Provenance is very important with data

License compliance/attribution tracking
Challenges in legalities

- Securing data sets can be a problem

There are gaps that have to be filled by extrapolating
Hard to find quality data collection and data as needed
Some data is unreliable, or critical data hasn’t been obtained

Costs/values/constraints (mostly about land)
- Trying to put value on land

Trade-offs with food, land and culture
Cultural aspects in nexus modelling are new, but destruction of the environment/land has been looked into.

- Issue: how do we get these factors included into the model (monetization or constraints)

It is hard to put a price on land, and also hard to put value on it.

- Semantics issue: Different countries account for the value of land differently. SDGs are usually on a global level (lots of mess)
- We can model what is easily quantified and measured, but how do we take into account what is (arguably) not easy to quantify

Examples: equity, justice, cultural preferences
Different possible approaches:
- Take model outputs (cost optimization), and then talk about the implications for other aspects
- Incorporate these aspects into the model
  - Take outputs then post-process through justice lens
  - Probably not the best way, but some think that you can reduce everything to a cost + put it into constraints (works with some things (e.g. value of statistical life) but not with others (e.g. gender equity))

- Value of land (brown fields vs biodiverse + cultural spaces)
- Weights

Building ‘weights’ is similar to putting a numerical value on these lands. From a computer perspective, it is essentially putting two different costs to these lands.

- Biodiversity

Reality: not a dollar value
With a cost benefits analysis, you always end up with some kind of value

- Is quantification possible?

Example: farmlands may be quantifiable, but spiritual valued land not so much

- Putting in numbers is okay, but they are highly uncertain, need to do sensitivities, test how robust results are due to assumptions (part of the job)
- Mix of ‘naturally quantifiable’ objectives (not necessarily in money)
  - Even capital and operational costs are not fully comparable
* Does not account for cash flow
* Lots of interest in how to bring these into cost benefit analysis
* Looking at full system costs (costs of building loads of solar and wind: trampling on cultural lands and biodiverse land, farmland and food production)
* These costs are not accurately factored into the models
* True cost of some of this transition is a lot higher than what people understand it to be
* Poor decisions can lead to even costlier results
* Combination of optimization and constraints
  * We could use this combination, but then we would have to also reach consent for land use in courts (this will not be numerical)
  * Can legal constraints be put into models as constraints?
  * We could get marginal cost out of model for that constraint (if it is a linear model)
* Costs and values of technologies to the system
  * Cost: Kwh from solar plant = 
  * Value: Power gained from solar plant when sun is shining
  * How do we include values and costs in models?
* Cost vs constraints
  * Cost: Costs from SDGs are going to interact with all the other cost functions, so unless you make them astronomically high, there is no guarantee
  * Constraints: Guaranteed outcome
* Cost and constraints (blend)
  * Subsidies for brown fields
  * Penalties for pristine areas
  * Emotionally driven -> always subjective
* Using penalties/method of using costs: two fold problems
  * If the penalties are not high enough, it may not be enough incentive
  * Social side: Is there such thing as 'barren' or 'waste land'? There are people who use this land but do not own it (often the lowest income). Are people going to get kicked off that land (are you kicking off the most marginalized)
* Example: New Zealand
  * No pricing, just a respect for different uses and dialogue that is ultimately mediated by the courts
  * Indigenous people and government scientists have a partnership
  * This worked well in New Zealand because of its legal framework, but in places without (or with more corruption) it is usually the poor suffering (people without knowledge to stand up for themselves, people without representation)
  * It is the responsibility of modellers to take those aspects into consideration. 'A moral duty to defend them'
* Example: Uganda's CLEWS model
  * Problem with land and infrastructure projects (constitution that the land belongs to the people). Has to be built with constitution/legality
  * Land acquisition (has to go through the government), exorbitant prices, infrastructure delayed
  * The costs of acquisition is not factored into the CLEWS model, but probably can be taken up
  * Biodiversity sensitive areas have special status, and those around them as well
  * Impacts on the land/life—have greater attention
  * They are not modelled explicitly (just 'off limits'), block modelling.
* Socio-technical modelling tools
  * Social things are out of a modeller's control, you cannot measure certain things
  * Human reactions/emotions might have a bigger guidance on policy decision making
  * Most of these modelling techniques are scenario driven
  * Missing links in literature (have not seen any paper looking at feedbacks between sectors)
  * They do not assign equal weights in the feedbacks
  * Representation: Nexus papers for an energy model will have some representation of water, but not as detailed compared to energy. This affects the insights that can be gained from the model.
  * Feedback loop's inequalities lead to problematic results and insights
    * Example: feedback between water, climate, and energy—does not look at implications from an economic perspective
  * Summary: 'Nexus modelling'—the results and insights can be problematic because the feedback loop inequalities within the model construction have not been carefully considered
  * System dynamics modelling, designed to capture influences, but it is difficult to calibrate
  * Avoiding paralysis
    * Sometimes proposing for change is seen as impossible or there are disagreements in processes, so nothing is done
  * Trade-offs are determined by decision makers (explicit or implicit)
    * Ultimately comes down to emotional weighting, not computation/quantification
  * Challenge: getting grants on socio-technical research
    * Because it is not precise, different than what is typically funded
  * Biophysical vs socio-technical
    * Biophysical systems—want highest accuracy possible
  * Socio-technical systems—have to involve as wide and diverse a group into the process
  * Open source movement, citizen assemblies, get a diverse range of perspectives and include these in the model.
• Stakeholders
  • Best practice: making sure the right stakeholders are involved
  • We should do model mediated public processes, citizen assemblies, etc
  • There should be a modelling team on hand, model mediated—these are yet to happen
  • Example: Berlin—there was supposed to be a mock citizens assembly once (model mediated analysis), but it fell through unfortunately
  • Need to bring in a larger range of people.
  • Design of models to address SDGs
    * Three different design choices

Multiple individual models (each designed to address an SDG), and combining them
Using model output to understand the implications for other SDGs (post-process)
Using SDGs as constraints in optimization models

• No clear lines in definitions
• Incorporating SDGs

Some are more easily incorporated than others
Life on land (easier) or carbon (easier) vs. biodiversity (maybe?) vs. gender or hunger (hard)

• For the harder to incorporate SDGs:
Can’t put all of them into cost functions or constraints
Linked to other measurable outcomes with constraint?
Linkage function that tells you if it will lower biodiversity index, with constraint on how low it can go?
Always going to have some form of translation process, or end up with crude ways of enforcing it (rough constraint)

Spatial scale
• At what spatial scale are these outcomes being measured?
  * Example: at a national level, and outcome meets a constraint, but at a smaller spatial scale, it may not
  * Ability to effectively trade off constraints to meet global targets
• Aggregation of spatial scales
  * Looking at where + under what conditions are we meeting constraints.
• COVID-19
  * People can make fast changes in their lives
  * We have less money than we thought, and limited resources.
• Simple or lightly coupled models
  * There are benefits to these
  * Use simple models to think about a problem

Does not mimic real world, but can get insights.

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