A REVIEW OF LESSONS FROM COMBINED MODELLING APPROACHES IN ASSESSING ENERGY AND CLIMATE POLICIES

Nastaran Arianpoo[1]*, Kamaria Kuling[2], Andrew S. Wright[1], Taco Niet[2]

[1] Faculty of Environment, Simon Fraser University, Technology and Science Complex 2 (TASC2), Suite 8800, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada

[2] School of Sustainable Energy Engineering, Simon Fraser University, 5118 - 10285 University Drive, Surrey, BC, V3T 0N1, Canada

Note: Portions of this paper, originally prepared IAEE in June of 2020, were subsequently incorporated into the final report for the Canadian Social Sciences and Humanities Research Council (SSHRC) Grant 872-2019-1009.

Abstract

The migration of the current energy system towards a system with a high penetration of renewable energy sources is necessary if the catastrophic impacts of climate change are to be prevented. The interdependencies of such energy system security to the human and ecosystem well-being calls for a more cross-disciplinary analysis of the policy space as recommended in the nexus approach. System modelling can play a significant role in addressing these complexities. However, this is best achieved if models expand their analysis horizon beyond the energy system and incorporate all nexus components. This paper developed a set of evaluation approaches to map the gaps in the adequacy of existing energy system models' capabilities and potentials in representing the nexus concept.

Keywords: Review, Energy transition, Combined modelling approach, Nexus concept, Energy Modelling

Introduction

Migration of the current energy system from fossil fuels to a system with a high penetration of renewable energy sources is a necessity if the catastrophic impacts of climate change are to be prevented [1]. The transition will stimulate change in many sectors of the energy system in the next couple of decades, spanning consumer behavior (both industrial and individual), development and investment directions, as well as policy angles on adaptation and mitigation decisions [1]. Note that the interdependencies of such energy system security to the human well-being and ecosystem health calls for a more cross-disciplinary and inter-sectoral analysis of the policy space. Re-engineering the energy system requires that the future investment and policy decisions be coordinated across multiple sectors of society to gain a better understanding of the co-benefits, challenges, and direct and indirect trade-offs inherent in these decisions. The pace of such transition depends on a broad range of technical, social, political, environmental, and financial interactions.

Energy system modelling can play a significant role in addressing these complexities and in recognizing inter-sectoral trade-offs to ensure effective policy decisions. However, this is best achieved if models expand their analysis horizon beyond the energy system and incorporate the security of other inter-dependent resources. The nexus approach is defined to enhance the cross-disciplinary and intersectoral coherence between different domains. In the past decades, the energy model community has become more aware of the importance of expanding the intersectoral and cross-disciplinary analysis of their models beyond the energy system. Several energy models have tried 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 [2,3]. However, the majority of current energy system models take into account only modest aspects of these interconnected systems. Our review of current published combined modelling techniques shows that they often tend to focus upon expanding the operational resolutions of the energy system, overlooking further interactions between energy system policy and investment decisions with other human and ecosystem well-being. Figure 1 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.

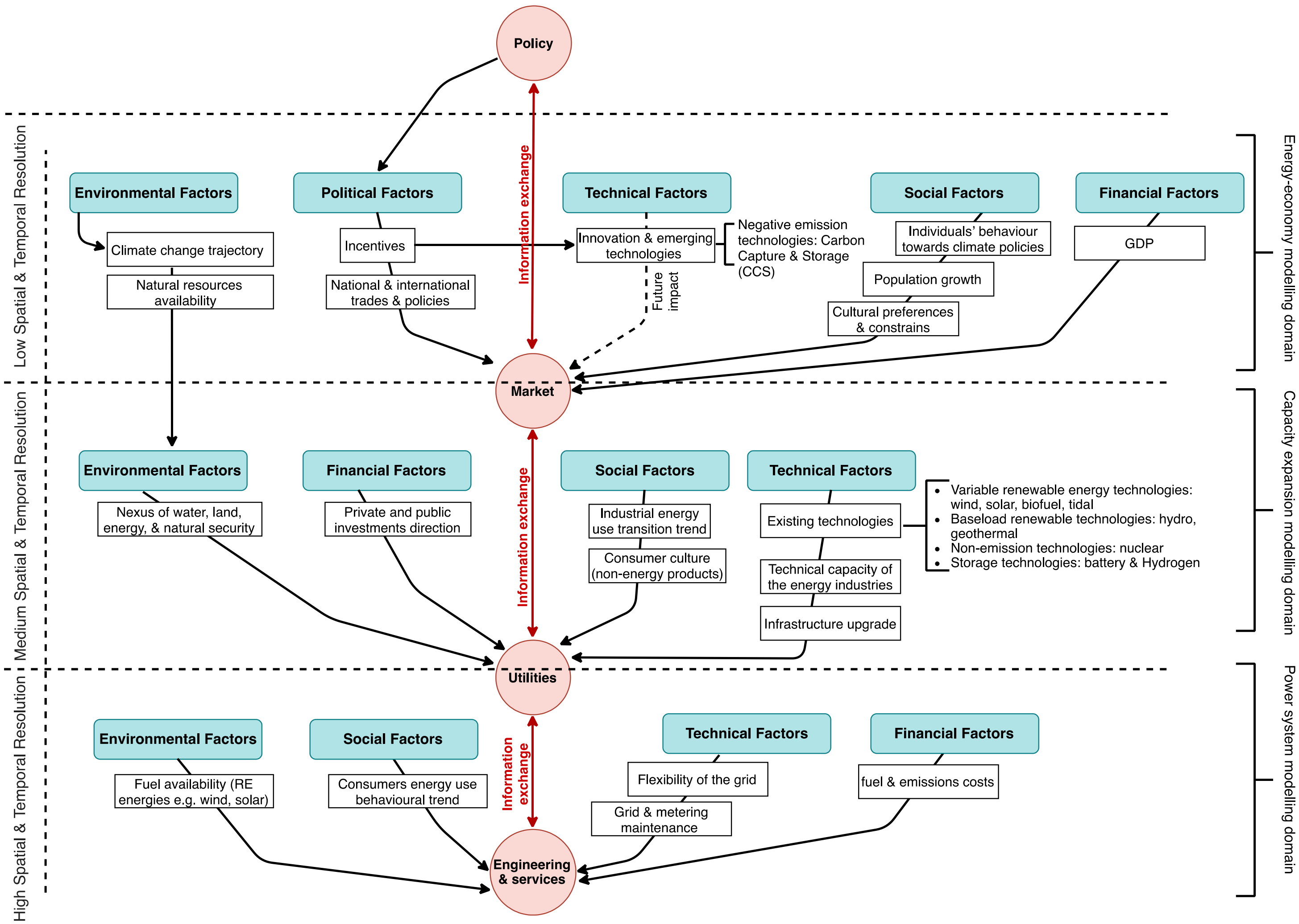

Figure 1: interaction of technical, social, environmental and financial factors in the power system

This paper evaluates the representation of the nexus concept within existing energy modelling approaches. It starts with exploring the conceptual definition of the nexus approach within the literature, its main components, and the factors by which its representation can be evaluated within the existing modelling approaches. Then, we review some of the different modelling paradigms in the literature and identify the specific questions and policies that each class of model structure can address. Existing combined models are then examined to identify the strengths and weaknesses of the expanded representations that include intersectoral and cross-disciplinaries considerations. Finally, we provide a consolidated overview of the potential interconnections between sectors and disciplines that still need consideration in the modelling literature.

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 due to the impacts of climate change, urbanization, and population growth [4]. 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 (water-energy-food nexus (WEF nexus)) [4]. 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. [1], [3]–[12]).

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 ([5,7]). Figure 2 illustrates some of the main components presented within the nexus literature in varied fields of nexus. Many of these factors and their linkages are not represented in the nexus 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 may become overlooked in policy recommendations. The red dashed circle in Figure 2 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.

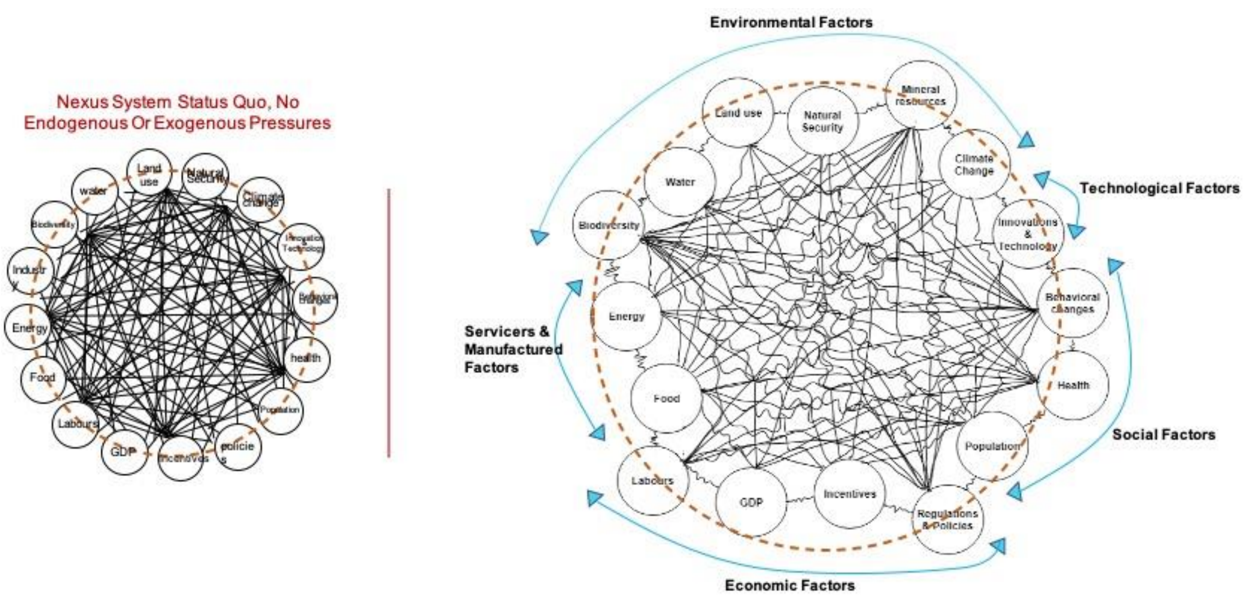

Figure 2: Conceptual illustration of interactions within the nexus system

In general, the term “nexus” is used to indicate the interactions among interdependent components [4]. 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.

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 [8]. Figure 2 is a simplistic representation of the nexus system. Qualifying and mathematically expressing many of these components and their interactions is a challenging task, mostly 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 [9].

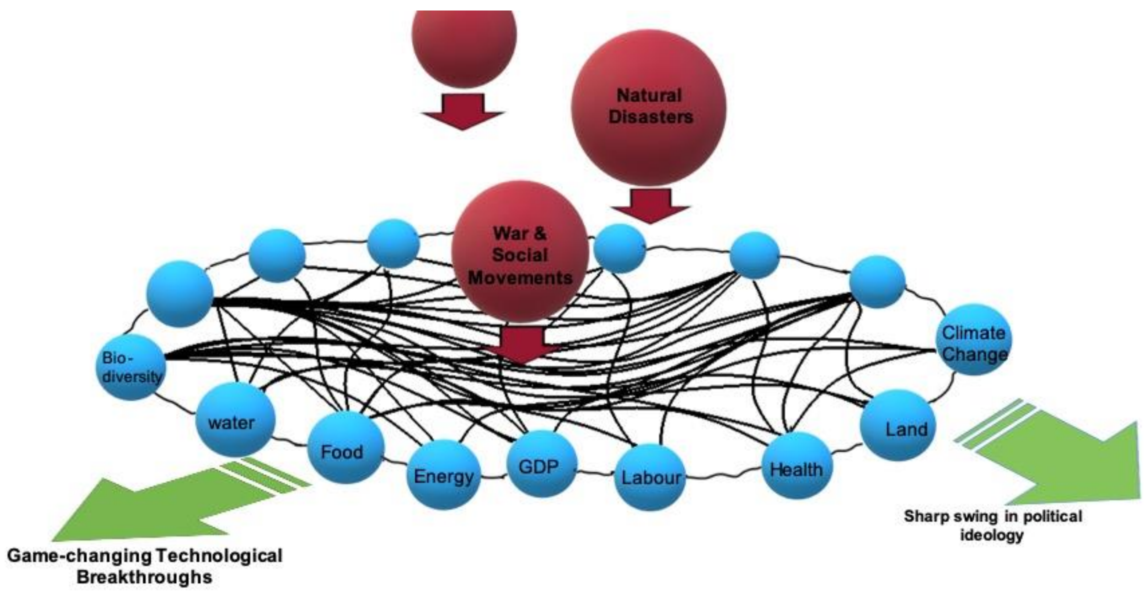

Figure 3: Interaction of exogenous and endogenous factors within the nexus system

As shown in Figure 3, 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 several social, political, and economic changes, such as the investment trajectory within the petroleum and renewable energy industries, as well as individual behavioral transitions in using public transportation. These unpredictable exogenous elements can push the whole system toward a new equilibrium, temporary or permanently. Currently, most models used for long-term planning (e.g. energy economy models) are incapable of exploring these extremes or capturing the political, social and cultural factors (as determinants of change) in their analysis. However, the fact that there are interdependencies that defy mathematical definitions or predictions based on traditional analysis methodologies does not mean they should not be explored in the models and future scenario simulations. Several energy models have tried to incorporate nexus elements into their analysis in the past decade, either by adding them to a single model or by linking models. The next sections of the paper evaluate representations of the nexus approach in the existing energy system modelling paradigms.

Energy Modelling Paradigms

There are three major classes of models used within the energy system modelling paradigms, as shown in Table 1. The first is the energy-economy model whose purpose is to simulate the human utilization of energy commodities and resources, and the impacts of policies, at the macro scale. CIMS [10] and GCAM [11] are examples of this type of model with a focus on the interaction of the behaviour of individuals with climate and energy policies (carbon pricing, flexible fuel standards, carbon trading). The general assumption inherent in these macro-economic models is that the agents are price-takers and that market equilibrium can be achieved. 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 [12,13].

The second types are the capacity expansion models. These 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 [10], and OSeMOSYS [14]. They typically have medium temporal (sub-yearly/seasonal) and spatial (regional) resolution and high technological detail.

Finally, power system models such as PLEXOS [15] and GTMax [13] 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.

Table 1: Energy system models and their modelling methodology

Models class	Modelling approaches	Main model examples	Analysis domain
Energy-economy models	Equilibrium (partial & general)	CIMS[16], GCAM [17], PRIMES [18], NEMS[19]	Forecasting scenario analysis and policy impact studies
Capacity expansion models	Optimization	OseMOSYS [14], MARKAL [10], Message [20]	Investment in capacity expansion and technologies in given energy system
Power system models	Optimization and simulation	PLEXOS [15], PowerFactory [21], GridCal [22], PyPSA[23]	Electricity market simulator

Table A.3, in appendix A, provides typical applications, strengths and weaknesses of the major models in the literature within each modelling paradigm. In Tables 1-4, only a few examples of models are chosen to represent and highlight the differences in the purposes and capabilities of energy-economy models, capacity expansion models, and power system models. For general comparison, similar to Table A.3 (Appendix A), a broader sample size can be found at [13], [14]. 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.

Combined Modelling Approaches

As Table A.3 (Appendix A) indicates, different energy models are designed to help address various questions regarding the policy, investment and engineering decisions. Because of this variety of purposes, they have various temporal and operational resolutions. Transferring to a power system with the high penetration of variable renewable energy sources requires engineering challenges that need to be considered and later reflected in future policy and investment decisions. While there is some overlap between the components covered by different models, as shown, there is no single model that covers all nexus qualities (high-temporal and operational resolutions as well as inter-sectoral and cross-disciplinary factors).

There have been several papers in recent literature where models from different modelling paradigms have been combined to address cross-sectoral challenges and/or to encompass different technical, spatial and/or temporal resolutions. These generally fall into the category of either combining capacity expansion and power systems models or combining energy-economy and capacity expansion models. Table B.4, in Appendix B, provides a glimpse into the common temporal and spatial resolutions differences within various single modelling classes with some example tools, as well as the accessibility (both calculation and solver) of these tools. The section then reviews the benefits and challenges of increasing the temporal and operational resolutions of energy system analysis using combined modelling approaches by reviewing some available examples within the literature.

Combined the Capacity Expansion and Power System Models

Providing capacity expansion models with the reliability, flexibility and grid security constraints estimated by the power system models have proven to be useful in informing decisions on power planning, policy, and new capacity expansion investments [24]. Capacity expansion models (CE) provide a long-term high-level trajectory of the evolving power system, reflecting both operational and investment considerations [24]. However, due to the computational limitations, CEs 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 [24] 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. [24] 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 (PS 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 [24].

Diakov et al. [24] 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 [25].

Deane et al.'s work [26] 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. [26] 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 generations. The results also showed that the convectional 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.

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 [12]. 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 [27] 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 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" [27]. 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. Figure 4 shows the flow of information in Després's work.

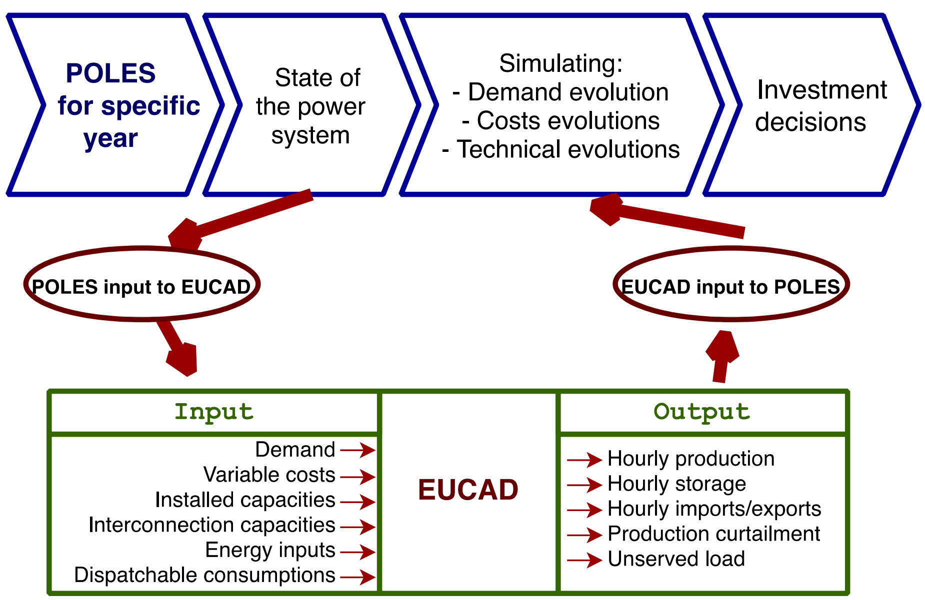

Figure 4: Després' work in 2015 [27]- Data exchange in combined modelling approach between POLES and EUCAD (Adapted from [27])

In Després' work [27], 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" [27]. 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 (Figure 4). 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 baseload fossil fuel sources (coal in European context), the renewable energy operational curtailments, flexibility options and investment directions in the pool of technologies.

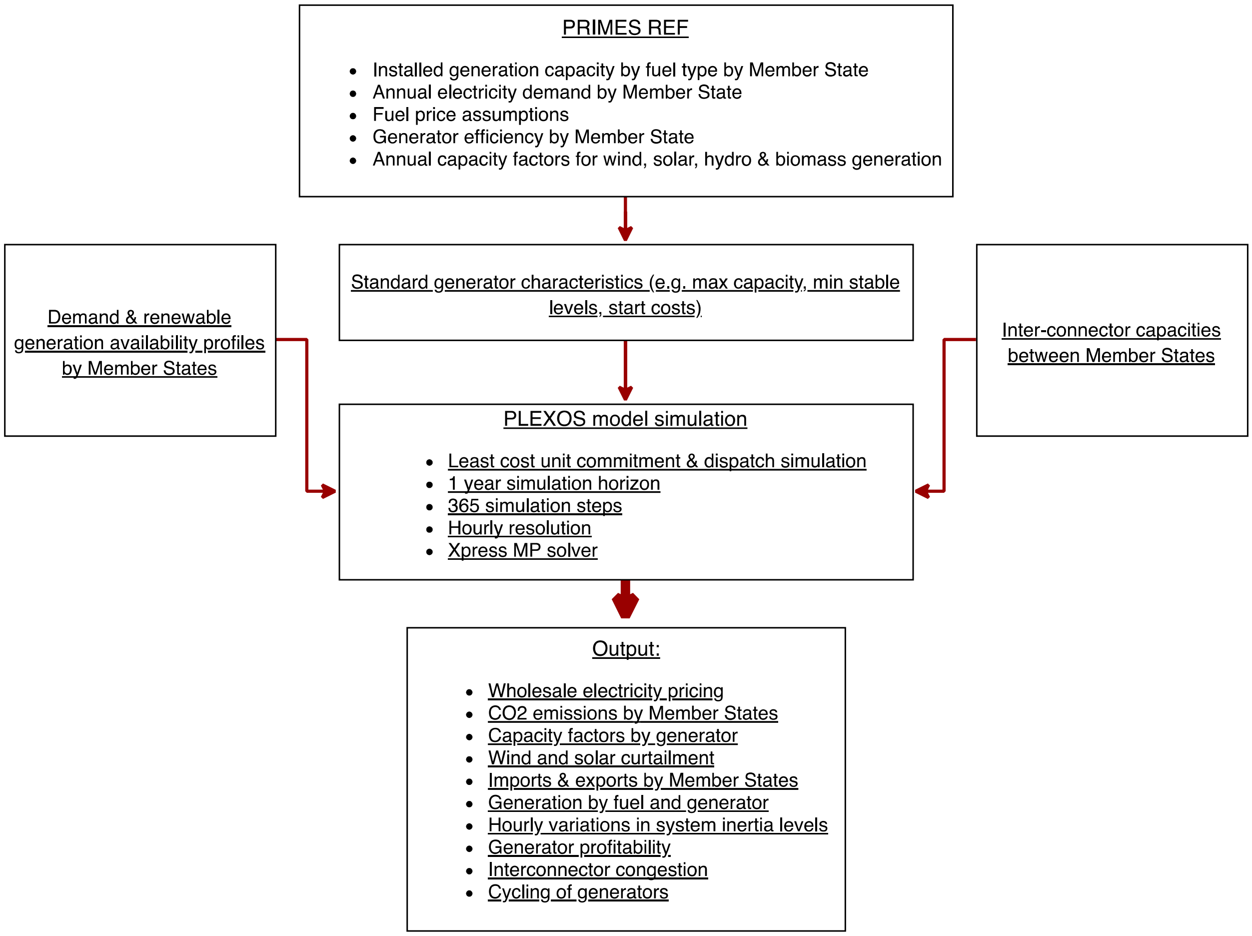

Figure 5: Collins et al.'s approach in 2017 [12]- flow of information between PRIMES and PLEXOS (Adapted from [12])

In 2017, Collins et al. [12] 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. Figure 5 shows the flow of information between PRIMES and PLEXOS according to Collins et al [12].

Collins et al.'s [12] 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, (power to gas, power to heat, and pumped hydro).

Table C.5, 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 C.5 (Appendix C) highlight the benefits that can be gained from generating the flow of information between energy-economy, capacity expansion, and power system models.

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. 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 [5], [6], [28], [7], [29]. 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 greenhouse gas 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. [5], [6], [28], [7], [29]). Climate, economy, minerals, land use, health, biodiversity security, waste, and technological advancements are examples of other dimensions [2], [30].

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 [2]. 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 [2]:

- 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 the third parties [2]. 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).

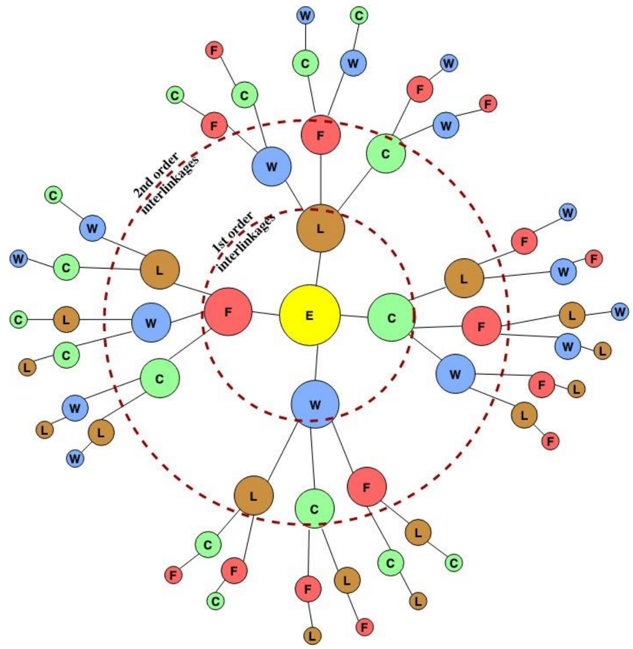

Figure 6: Nexus tree approach: direct and indirect interlinkages of energy with other components of five-dimensional nexus of energy, water, food, land use, climate (Adapted from [2])

Figure 6 illustrates the web of direct and indirect interlinkages between energy and other five-dimensional nexus components as defined in SIM4NEXUS project. A similar nexus tree diagram can be centered around each of the nexus components to explore all the interlinkages. Figure 7 shows all the direct and indirect ways that a change in energy status can impose on water status and vice-versa.

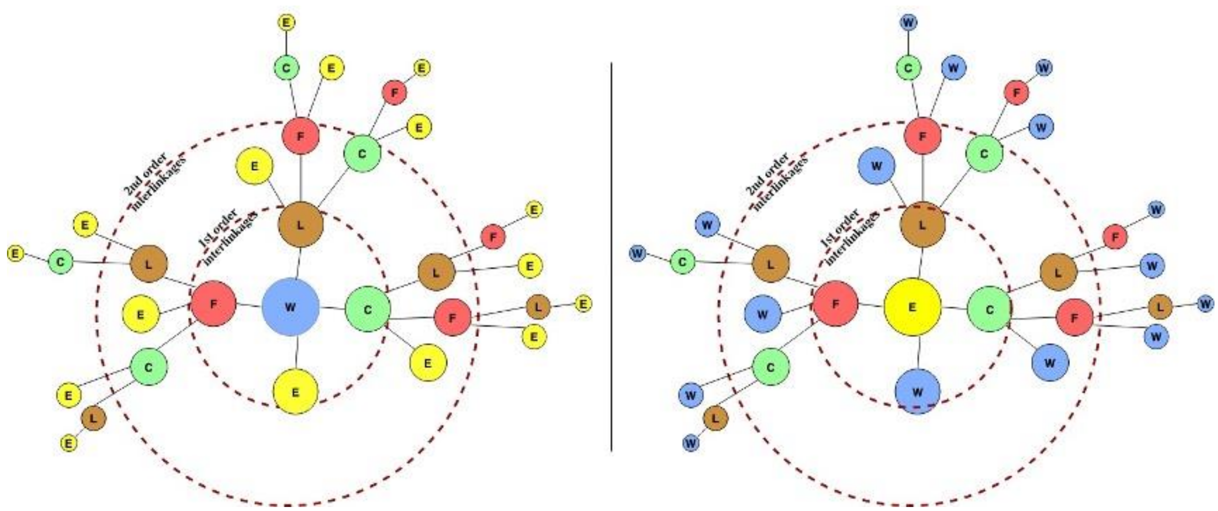

Figure 7: nexus tree approach: showing the direct and indirect interlinkages of energy with water and water with energy (Adapted from [2])

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 is intended to explore the quality of linkages and maps the current gaps within the existing models. The following notes need to be considered while examining the contents of the table:

- Note that 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.

- Note that although 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 paper. Checkmarks in this table 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 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 7.

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.

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, etc.), 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, etc.), their inputs are often provided exogenously or are there as tracking only data (e.g. tracking aggregate CO_2 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 nexus concept [31].

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 & F → L) [32]. 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→ Ec and Ec→ E)

Table 2: evaluating the representation of 1st order of direct linkages within the nexus of water-food-energy-land use- climate, plus economy

Model class	Model class branches		Representation of nexus component interlinkages within the model: 1st order of direct interlinkages + economy																										Economy (Ec)				
			Water (W)					Food (F)					Energy (E)					Land use (L)					Climate (C)									
			W ↓ F	W ↓ C	W ↓ L	W ↓ E	W ↓ Ec	F ↓ C	F ↓ L	F ↓ E	F ↓ W	F ↓ Ec	E ↓ W	E ↓ C	E ↓ F	E ↓ L	E ↓ Ec	L ↓ E	L ↓ C	L ↓ W	L ↓ F	L ↓ Ec	C ↓ L	C ↓ E	C ↓ W	C ↓ F	C ↓ Ec	Ec ↓ W	Ec ↓ F	Ec ↓ E	Ec ↓ L	Ec ↓ C
Energy-economy	Base models	General equilibrium models (e.g. GEM-E3 & GTAP)												✓			✓													✓		
		Partial equilibrium models (e.g. CIMS & 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												✓																		

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 [3].

CLEWS is chosen as an example of expanded versions of the capacity system models. The model focuses on assessing interlinkages between resources of climate, land (food), energy, and water systems [33]. 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 & E → Ec).

Power System Model Class

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.

Discussion

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 A.3 (Appendix A), Table B.4 (Appendix B), and Table C.5 (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 [12]. 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 [12].

As highlighted in Table B.4 (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 [25,26], 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.

Combining modelling techniques can help to keep the computational complexity of the high temporal and operational resolutions manageable, while broadening the cross-sectoral scope of the model. The ultimate goal is to create feedback loops to test the accuracy of energy-related assumptions and simulations. A review of the existing literature on combined modelling approaches shows that such robust interaction and reciprocal feedback has been already developed between capacity expansion and power system models. The missing feedback in the existing literature is the interactive interlinkage between the energy economy and capacity expansion models.

Regarding the expansion of cross-disciplinary coverage of models, our research highlights that although there are some trade-offs when combining models, and some uncertainty in broadening the models' scope, combined modelling approaches have the potential to address policy questions beyond the boundaries, capabilities, and assumptions within any individual model. The nexus approach in modelling helps to better recognize the potential for implementation of solutions such as the low-carbon economies and achieve United Nations SD goals, and at the same time, to optimize the transition. Our findings indicate that while intersectoral interaction between energy economy, capacity expansion, and power system models are getting more attention, the cross-disciplinary interactions of energy domain with factors such as water, food, and natural securities remain relatively underrepresented in existing models. For instance, as shown in Table 2, all model classes lack representation of the direct interaction from water to the rest of the nexus components. Models often track the water-related policies as exogenous input (such as restrictions on water use), but they lack incorporating the competitions between components for available water. Considering that climate change is all about changes in the water cycle and water scarcity is one of the biggest challenges we are facing today, the absence of such vital interactions within tools that are expected to evaluate climate action policies is alarming.

It is important to note that today's economy is more complicated than to be represented as a close box similar to the way it is represented in energy-economy models and other partial equilibrium models. Many factors, including state of the energy sector, affect economic indicators such as GDP, and employment rate. However, as Table 2 highlighted, economic input for the models of different classes (except general equilibrium energy models) is often delivered exogenously without providing any interaction and feedback on the effect of various policy decisions back to the economy.

Combining modelling techniques can be beneficial in addressing modelling limitations in representing the nexus concept. Note that general equilibrium energy-economy models have very low temporal and technical resolutions due to their broad scope. As a result, they may not be an easy candidate for cross-disciplinary expansion as a single model. However, combining techniques to expand the temporal and operational of partial equilibrium energy models (energy-economy + capacity expansion + power system models) has shown promising results. Similar combining techniques can be used to combine models developed for the other sectors of the economy to create a full economic spectrum, as well as expanding the nexus coverages of the collective developed modelling system.

Conclusion

Decarbonization of our economy and its impact on the energy system requires an analysis that goes beyond the current boundaries of most established modelling paradigms. This paper suggested a set of evaluation approaches to map the gaps in the adequacy of existing energy system models, while emphasizing on developing models capable of incorporating all nexus components into their analysis. Such models will be better equipped to assist policymakers and provide a more accurate picture of climate change actions. Our review of the current energy system models' capabilities and potentials indicates two main gaps in existing models. The first gap is the limitation of the representation of an energy system with a high penetration of intermittent renewable resources. This can affect the accuracy of a model analysis in determining investment timing in new technologies, generation capacity, exploring cross-disciplinary trade-offs, and projecting the actual CO_2 emissions. The second gap is the inadequate incorporation of the nexus concept into energy systems' analysis; there is no single model that covers all nexus qualities shown in Table 2.

As review of case studies shows, the combined modelling approaches have the potential to help to close the above gaps. Closing the gap from theory to practice, however, seems to be not easy; as yet, there is ambiguity in the definition of the nexus, in the description of which interactions are needed to be represented within models, and how the interactions should be functioning. All these require further research.

Funding

This work was supported by the Willow Grove Foundation, Vancouver, Canada; and the Social Science and Humanities Research Council of Canada (SSHRC) - Knowledge Synthesis Grants, Canada.

Declaration of competing interest

The authors report no conflicts of interest.

Acknowledgements

The authors acknowledge the financial support received from Willow Grove Foundation, Canada, and Social Science and Humanities Research Council of Canada (SSHRC) for their support in carrying out this work.

References

[1] H. Yuan, P. Zhou, D. Zhou, What is low-carbon development? A conceptual analysis, in: Energy Procedia, Elsevier Ltd, 2011: pp. 1706–1712. https://doi.org/10.1016/j.egypro.2011.03.290.

[2] C.S. Laspidou, D.T. Kofinas, N.K. Mellios, M. Witmer, Modelling the Water-Energy-Food-Land Use-Climate Nexus: The Nexus Tree Approach, Proceedings. 2 (2018) 617. https://doi.org/10.3390/proceedings2110617.

[3] F. Brouwer, G. Avgerinopoulos, D. Fazekas, C. Laspidou, J.F. Mercure, H. Pollitt, E.P. Ramos, M. Howells, Energy modelling and the Nexus concept, Energy Strateg. Rev. 19 (2018) 1–6. https://doi.org/10.1016/j.esr.2017.10.005.

[4] Z. Khan, P. Linares, J. García-González, Integrating water and energy models for policy driven applications. A review of contemporary work and recommendations for future developments, Renew. Sustain. Energy Rev. 67 (2017) 1123–1138. https://doi.org/10.1016/j.rser.2016.08.043.

[5] N. Weitz, C. Strambo, E. Kemp-Benedict, M. Nilsson, Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance, Glob. Environ. Chang. 45 (2017) 165–173. https://doi.org/10.1016/j.gloenvcha.2017.06.006.

[6] S. Shannak, D. Mabrey, M. Vittorio, Moving from theory to practice in the water–energy–food nexus: An evaluation of existing models and frameworks, Water-Energy Nexus. 1 (2018) 17–25. https://doi.org/10.1016/j.wen.2018.04.001.

[7] N. Weitz, C. Strambo, E. Kemp-Benedict, M. Nilsson, Governance in the water-energy-food nexus: Gaps and future research needs, 2017.

[8] S. Hosseini, K. Barker, J.E. Ramirez-Marquez, A review of definitions and measures of system resilience, Reliab. Eng. Syst. Saf. 145 (2016) 47–61. https://doi.org/10.1016/j.ress.2015.08.006.

[9] A. Smajgl, J. Ward, L. Pluschke, The water-food-energy Nexus - Realising a new paradigm, J. Hydrol. 533 (2016) 533–540. https://doi.org/10.1016/j.jhydrol.2015.12.033.

[10] T. Nakata, D. Silva, M. Rodionov, Application of energy system models for designing a low-carbon society, Prog. Energy Combust. Sci. 37 (2011) 462–502. https://doi.org/10.1016/j.pecs.2010.08.001.

[11] GCAM v4.2 Documentation: GCAM Model Overview, (n.d.). https://jgcri.github.io/gcam-doc/v4.2/overview.html (accessed January 22, 2020).

[12] S. Collins, J.P. Deane, B. Ó Gallachóir, Adding value to EU energy policy analysis using a multi-model approach with an EU-28 electricity dispatch model, Energy. 130 (2017) 433–447. https://doi.org/10.1016/j.energy.2017.05.010.

[13] S. Collins, J.P. Deane, K. Poncelet, E. Panos, R.C. Pietzcker, E. Delarue, B.P. Ó Gallachóir, Integrating short term variations of the power system into integrated energy system models: A methodological review, Renew. Sustain. Energy Rev. 76 (2017) 839–856. https://doi.org/10.1016/j.rser.2017.03.090.

[14] OSeMOSYS (Open Source Energy Modelling System), About - OSeMOSYS, (2008). http://www.osemosys.org/about.html (accessed January 22, 2020).

[15] W. Lise, Energy sector modelling tools and their functionalities, Ankara, 2019. https://scenarios2013.enerjiprojeleri.eu/Dosyalar/Etkinlikler/Training 2/Day 1 - Energy Sector Modelling Tools and Their Functionalities.pdf (accessed March 26, 2020).

[16] G. Wood, Forecasting & measuring outcomes of energy efficiency & GHG emission reduction initiatives macro models and data review, Energy Navig. Conculting. (2011). https://www.exec.gov.nl.ca/exec/occ/publications/macro_models_mitigation_initiatives.pdf (accessed March 26, 2020).

[17] K. Bishkek, Overview of the Global Change Assessment Model (GCAM), 2018. https://www.unece.org/fileadmin/DAM/energy/se/pdfs/CSE/PATHWAYS/2019/ws_Consult_14_15.May.2019/supp_doc/PNNL-GCAM_model.PDF (accessed March 26, 2020).

[18] P. Capros, PRIMES ENERGY SYSTEM MODEL, (2011). https://www.plan.be/uploaded/documents/PRIMES.pdf (accessed March 19, 2020).

[19] U.S. Energy Information Administration, Availability of the National Energy Modeling System (NEMS) Archive, (n.d.). https://www.eia.gov/outlooks/aeo/info_nems_archive.php (accessed March 26, 2020).

[20] International Institution for Applied Sysytem Analysis (IIASA), MESSAGE, (2019). https://iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html (accessed March 26, 2020).

[21] DIgSILENT, PowerFactory 2020 product specification, (2020). https://www.digsilent.de/en/downloads.html?folder=files%2Fdownloads%2Fpublic%2F10_PowerFactory%2F50_Product+Specification#navigation573 (accessed April 2, 2020).

[22] S.P. Vera, Theory behind GridCal , (n.d.). https://gridcal.readthedocs.io/en/latest/theory/models.html (accessed April 2, 2020).

[23] H.K. Ringkjøb, P.M. Haugan, I.M. Solbrekke, A review of modelling tools for energy and electricity systems with large shares of variable renewables, Renew. Sustain. Energy Rev. 96 (2018) 440–459. https://doi.org/10.1016/j.rser.2018.08.002.

[24] V. Diakov, W. Cole, P. Sullivan, G. Brinkman, R. Margolis, Improving Power System Modeling: A Tool to Link Capacity Expansion and Production Cost Models, 2015. www.nrel.gov/publications. (accessed January 22, 2020).

[25] N. Blair, E. Zhou, D. Getman, D.J. Arent, Electricity Capacity Expansion Modeling, Analysis, and Visualization: A Summary of Selected High-Renewable Modeling Experiences, 2015. www.nrel.gov/publications. (accessed January 22, 2020).

[26] J.P. Deane, A. Chiodi, M. Gargiulo, B.P. Ó Gallachóir, Soft-linking of a power systems model to an energy systems model, Energy. 42 (2012) 303–312. https://doi.org/10.1016/j.energy.2012.03.052.

[27] J. Despres, Development of a dispatch model of the European power system for coupling with a long-term foresight energy model, 2015. http://hal.univ-grenoble-alpes.fr/hal-01245554 (accessed April 8, 2020).

[28] N. Weitz, M. Nilsson, M. Davis SAIS, A Nexus approach to the post-2015 agenda: Formulating integrated water, energy, and food SDGs, Rev. Int. Aff. 34 (2014) 37–50. https://doi.org/10.1353/sais.2014.0022.

[29] S. Villamayor-Tomas, P. Grundmann, G. Epstein, T. Evans, C. Kimmich, The water-energy-food security nexus through the lenses of the value chain and the institutional analysis and development framework, n.d. www.water-alternatives.org (accessed August 17, 2020).

[30] T. Niet, N. Arianpoo, K. Kuling, S. Wright, Andrew, The need for expanding the modelling nexus: an analysis of the sustainable development goals, in: Int. Energy Work., Freiburg, Germany, 2020.

[31] N. Rivers, M. Jaccard, Useful models for simulating policies to induce technological change, Energy Policy. 34 (2006) 2038–2047. https://doi.org/10.1016/j.enpol.2005.02.003.

[32] K. Calvin, P. Patel, L. Clarke, G. Asrar, B. Bond-Lamberty, R.Y. Cui, A. Di Vittorio, K. Dorheim, J. Edmonds, C. Hartin, M. Hejazi, R. Horowitz, G. Iyer, P. Kyle, S. Kim, R. Link, H. McJeon, S.J. Smith, A. Snyder, S. Waldhoff, M. Wise, GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems, Geosci. Model Dev. 12 (2019) 677–698. https://doi.org/10.5194/gmd-12-677-2019.

[33] CLEWS - Home, (n.d.). http://www.osimosys.org/ (accessed June 11, 2020).

[34] E3mlab/ICCS, PRIMES MODEL 2013-2014 Detailed model description, 2014. http://www.e3mlab.euCentral@e3mlab.eu (accessed March 31, 2020).

[35] K. Calvin, S. Pachauri, E. De Cian, I. Mouratiadou, The effect of African growth on future global energy, emissions, and regional development, Clim. Change. 136 (2016) 109–125. https://doi.org/10.1007/s10584-013-0964-4.

[36] R. Murphy, A. Pardy, T. Budd, Interactions of policies acting at the local, sub-national, and national scales for Canada's energy transition, 2019. https://emi-ime.ca/wp-content/uploads/2020/02/SFU_Murphy_Jaccard_Griffin_Pardy_Budd_Interactions_Of_Policies_At_Different_Scales.pdf (accessed March 26, 2020).

[37] OnLocation Consulting Inc., What can the NEMS model do and what can't it do?, (n.d.). https://www.onlocationinc.com/blog/what-can-the-nems-model-do-and-what-cant-it-do (accessed March 26, 2020).

[38] US Energy Information Administration (EIA), Impacts of a 25-percent renewable electricity standard as proposed in the American Clean Energy and Security Act discussion draft, 2009.

[39] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. DeCarolis, M. Bazillian, A. Roehrl, OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development., Energy Policy. 39 (2011) 5850–5870. https://doi.org/10.1016/j.enpol.2011.06.033.

[40] M. Welsch, M. Howells, M. Bazilian, J.F. DeCarolis, S. Hermann, H.H. Rogner, Modelling elements of Smart Grids - Enhancing the OSeMOSYS (Open Source Energy Modelling System) code, Energy. 46 (2012) 337–350. https://doi.org/10.1016/j.energy.2012.08.017.

[41] M.R.F. Zonooz, Z.M. Nopiah, A.M. Yusof, K. Sopian, A review of MARKAL energy modeling, Eur. J. Sci. Res. 26 (2009) 352–361. https://www.researchgate.net/publication/265152928_A_review_of_MARKAL_energy_modeling (accessed April 1, 2020).

[42] iea-etsap, MARKAL, (n.d.). https://iea-etsap.org/index.php/etsaptool/model-generators/markal (accessed March 26, 2020).

[43] J. Krzemień, Application of Markal model generator in optimizing energy systems, J. Sustain. Min. 12 (2013) 35–39. https://doi.org/10.7424/jsm130205.

[44] N.H. Mirjat, M.A. Uqaili, K. Harijan, G. Das Valasai, F. Shaikh, M. Waris, A review of energy and power planning and policies of Pakistan, Renew. Sustain. Energy Rev. 79 (2017) 110–127. https://doi.org/10.1016/j.rser.2017.05.040.

[45] E. Wright, J.A.B. Belt, A. Chambers, P. Delaquil, G. Goldstein, A power sector analysis for Cuba using the MARKAL model 1, ASCE. 19 (2009). http://www.eia.doe.gov/oiaf/aeo/ (accessed March 26, 2020).

[46] H.-H. Rogner, IIASA's Integrated Assessment Framework, (2016). https://www.unece.org/fileadmin/DAM/energy/se/pp/cse_pathways_ws3.2016/4_Rogner.pdf (accessed March 26, 2020).

[47] International Institute for Applied Systems Analysis (IIASA), Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), (n.d.). http://webarchive.iiasa.ac.at/Research/ENE/model/message.html (accessed March 26, 2020).

[48] Energy Plan, MESSAGE , (n.d.). https://www.energyplan.eu/othertools/global/message/ (accessed April 1, 2020).

[49] IIASA Energy Program, message Documentation Release 1.0, 2020.

[50] B. Kichonge, G. R John, I. S N Mkilaha, Modelling energy supply options for electricity generations in Tanzania, (n.d.). http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1021-447X2015000300005 (accessed March 26, 2020).

[51] P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B. R Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield, Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development Supplementary Material. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenh, 2018.

[52] T. Forrest, hydro cascade & storage optimisation utilising PLEXOS , n.d. https://energyexemplar.com/wp-content/uploads/02-15-Price-Forecasting-Forum-Berlin_-TF_Final.pdf (accessed March 26, 2020).

[53] A. Chiodi, J.P. Deane, M. Gargiulo, B.P.Ó. Gallachóir, Modelling electricity generation-comparing results: from a power systems model and an energy systems model, 2011. https://www.researchgate.net/publication/228822212_Modelling_Electricity_Generation-Comparing_Results_From_a_Power_Systems_Model_and_an_Energy_Systems_Model (accessed March 26, 2020).

[54] J.P. Deane, E.J. McKeogh, B.P. Ó Gallachóir, Derivation of robust storage targets for large scale pumped hydro energy storage using PLEXOS, Hammersmith, London, 2010. https://old.energyexemplar.com/wp-content/uploads/publications/Derivation of Robust Storage Targets for Large Scale Pumped Hydro Energy Storage using PLEXOS.pdf (accessed March 26, 2020).

[55] M. Stifter, R. Schwalbe, F. Andren, T. Strasser, Steady-state co-simulation with PowerFactory, in: 2013 Work. Model. Simul. Cyber-Physical Energy Syst. MSCPES 2013, 2013. https://doi.org/10.1109/MSCPES.2013.6623317.

[56] Joint Global Change Research Institute, GCAM Model Overview, (n.d.). https://jgcri.github.io/gcam-doc/overview.html (accessed April 1, 2020).

[57] S. Oberle, R. Elsland, Are open access models able to assess today’s energy scenarios?, Energy Strateg. Rev. 26 (2019) 100396. https://doi.org/10.1016/j.esr.2019.100396.

[58] U.S. Energy Information Administration (EIA), The National Energy Modeling System: An overview 2018, Washington, DC, 2019. https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581(2018).pdf (accessed April 1, 2020).

[59] The MESSAGEix framework — MESSAGEix 3.0.1 documentation, (n.d.). https://message.iiasa.ac.at/en/stable/ (accessed June 14, 2020).

Appendix A

Table A.3: Main existing models in each level of energy system and their main sectoral focus

Table A.4: 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) [18,23,34]	Partial equilibrium model Hybrid model, embedding technologies in economic decisions [34] Designed as modularity (separate modules for each S&D [1] sector) [18], price-induced market equilibrium system [23]	• Detailed energy system projection • Impact assessment for energy and environment policies • Energy-economy-environment policy analysis in linked to GEM-E3 (Macroeconomic/sectoral activity model) and GAINS (Air Pollution Interactions and Synergies) models	• The distinctive feature of PRIMES is its hybrid representations of both bottom-up (engineering, explicit technology choices) and top-down (microeconomic foundation of economic decisions by agent) [18] • Market orientation • Focus on demand side behaviors [34]	• Due to its partial equilibrium nature of the model, it lacks closed-loop energy-economy equilibrium analysis. This means the equilibrium stablished between supply and demand in each scenario can't send a feedback to the rest of the economy [34] • Only scenario projections not forecasting • Lack of high spatial resolutions below country level • Lack of high operational/engineering resolution and representation, so cannot deliver short-term engineering analysis [18]	Economy-engineering Electricity and gas trade within EU international market Behavioural model that captures: • Demand • Supply • Pollution abatement technologies related to energy use	[12]	Similar model in capability: NEMS used by US-EIA/DOE [18] – PRIMES developed based one the needs of European energy system while NEMS is based on USA energy system
	GCAM [17] (Global Change	• Partial equilibrium model (price-induced model system)	• 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	• 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	[35]	

[1] S&D: supply and demand

Model class	Sample of modelling tool	Modelling paradigm	Typical Application/Analysis	Strength	Limitation	Sectoral Focus	More info.	Note
	Assessment Model)	• Defined by its developer as a global integrated assessment model (IAM)2 [17]	• Explore the role of uncertainty in shaping events • Simulation of future carbon emissions	climate [17] (mostly exogenously) • Combination of modular structure and open-source software allows modelers to modify the model based on their specific needs	• Lack of high spatial resolution in open-source version (Not country specific) • Runs at 5-year intervals • Population growth and GDP are fixed	• Water supplies: 384 sub-regions • Physical earth system: global [17]		
	CIMS [16]	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 [16]	• energy supply • energy-intensive industries • key energy end-uses in the residential, commercial/institutional • transportation sectors	[36]	
	NEMS (National Energy Modelling System)	• Partial Equilibrium • Energy-economy modeling system • Defined by its developer as	Projection and simulation of the energy, economic, environmental, and security impacts of alternative energy policies through scenarios	It includes behavioral and technological choices criteria	• Lack of high operational/engineering resolution • Lack of representing technologies with current abroad small market potential [37] • Lack of spatial resolution for state-level analysis and poor global application [19]	• Electricity and heat [23] • National energy policies • Power sector • Residential and commercial building sectors • Transportation sector	[38]	Similar model in capability: PRIMES [18] but designed for the United States

[2] 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.

Model class	Sample of modelling tool	Modelling paradigm	Typical Application/Analysis	Strength	Limitation	Sectoral Focus	More info.	Note
		Integrated assessment model2				• Oil and gas recovery • Petroleum product and their substitutes [37]		
Capacity expansion models	OseMOSYS (The Open Source Energy Modeling System)	• Bottom-up linear programming (LP) • System optimization model	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 [39]	• 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) • Designed as a research/training model • It allows a test-bed for new energy model developments [39] • Since it is an open-source model, it can be easily updated and modified to suit the needs of a particular analysis and modeler [39]	• As a LP model, it does not take the effect of uncertainty and time into consideration • As an LP model, many parameters are assumed to be constant which is far from reality • Limited to a single object at the time, while in reality situations are often multi-objective interactions	Core model represents the power system, but structure allows extensions of the model to other sectors	[40]	Welsch et. al. [40] 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)
	MARKAL (MARKet and Allocation) [41]	• Linear Optimisation • Partial Equilibrium [23] •	• Least-cost energy systems planning considering policies, taxes, subsidies • Project impacts of system on future emissions • Compare scenarios with and without regional cooperation [42]	• Applies from global scale to isolated local energy systems [23]	• Input data that completely describes the system can be challenging to obtain [43] • Extensive training and experience required. [44]	• Energy system planning and system costs • Costs and system impact of policy, environmental restrictions, taxes, subsidies.	[45]	

Model class	Sample of modelling tool	Modelling paradigm	Typical Application/Analysis	Strength	Limitation	Sectoral Focus	More info.	Note
	MESSAGE (Model of Energy Supply Systems And their General Environmental Impact	• Systems engineering optimization model (all GHGs, all energy sectors, water) [46]	• 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" [20]	• Represents all aspects of the energy system from extraction/imports/exports to end-use services [47] • Has user-controlled time horizon for analysis [44] • Flexible [44]	• "Difficult troubleshooting, low clarity of user manual, very tricky data input, level of difficulty in running model is higher" [44] • Inputs for the model are detailed on the supply side but the demand inputs are more aggregated [48] • 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) [20], 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 [49]	[50]	• Used in preparation of several IPCC reports , such as 2018 [51]
Power system models	PLEXOS	• Market simulation software[15] • Deterministic and stochastic optimization methodology (Mixed-Integer, Linear and Non-Linear) [23] • Electricity market modeling and planning	• Minimization of overall system operational cost • Capacity expansion & investment planning • Market Analysis or Design • Price forecasting and risk analysis • Portfolio optimisation and valuation • Transmission and ancillary services analysis • Renewable integration analysis & optimisation • Integrated electric and gas system market modelling • Co-optimisation of other commodities (Water, Heat etc.)"[52]	• Pre-calibrated by the developer for many situations • Robust simulation capabilities across electric, water and gas systems • Focusing on full user control, transparency and accuracy across numerous constraints and uncertainties • Has many users among Public institutions, commercial companies, utilities, universities, among others" [15] • free for non-commercial research to academic institutions [53]	Expensive for non-commercial applications [15]	Electricity system planning and operation can co-optimize: • Thermal • Hydro • Energy/reserve/fuel markets • Contracts	[54]	
	PowerFactory	Network power management model	• Analysing generation • Transmission, distribution	• Not specified in available document	• Not specified in available document	Power distribution Power transmission Industrial system Power generation	[55]	

Model class	Sample of modelling tool	Modelling paradigm	Typical Application/Analysis	Strength	Limitation	Sectoral Focus	More info.	Note
			• 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 unite 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	Distributed generation Renewable integration		
	GridCal	Research oriented power systems software	"Design and implementation of electrical calculation software (power flow, short circuit, voltage collapse, stochastic calculation and network collapse)" [22]	• 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		
	PyPSA (Python for Power System Analysis)	• simulation and optimization of electrical power systems	"Investment & operation decision support, power system analysis tool (Power Flow and Contingency Analysis)" [23]	• 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		

Appendix B

Table B.5: Temporal and spatial resolutions of modelling approaches and their accessibility

Models class	Sample of modelling tools & approaches	Temporal resolutions	Current temporal extent	Spatial resolutions	Current spatial extent	Open source	
						Model[3]	**Solver**
Energy-economy models (EE)	PRIMES [18,23,34]	Low: 5 years' time-step	2000 - 2050	Medium to long-term analyses that span over decades	• Europe: country-by-country in European context • Can also do analysis for multiple countries with endogenous electricity trade	Not specified in available documents	Not specified in available documents
	GCAM [56]	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 [57]	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 [16], Canada, China	Not specified in available documents	Commercial	Commercial

[3] Note that being an open source software varies from being free to access.

Models class	Sample of modelling tools & approaches	Temporal resolutions	Current temporal extent	Spatial resolutions	Current spatial extent	Open source	
						Model[3]	Solver
	NEMS [58]	Low: yearly (some component seasonal) [23]	2050 [23]	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" [19]	Not specified in available documents
Capacity expansion models (CE)	MARKAL	Multiple years of fixed length – (user can define time-slices within a year) [23]	Long-term: multiple years, usually 40-50	Local and regional	In 40 countries	Commercial	Only source code, needs additional commercial software [57]
	OSeMOSYS	Medium: Can be defined by user (usually seasonal, or intra-annual) [23]	User-defined [23]	Community to continental [23]	OSeMOSYS has been applied in at least 30+ countries	Open source	Yes
	MESSAGE	Multiple years (User-defined) [23] usually 5-10 year time-step [48]	Medium (1-5 years) to long-term (1-40 years with maximum of 120 years) [48]	National and global	Global and 11 nations [23]	• Available upon request [23] for academic purposes • Note: It comes in different variation, for instance, MESSAGEix is open source (but the solver is not) [59]	Not specified in available documents
Power system models (PS)	PLEXOS	Short to long-term: can be defined by user up to 1 min (Usually hourly) [23]	User-defined- from long-term (1-40 years) to medium-term (1-5 years) to short-term (less than 1 year) [23] [53]	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 [21]	Not specified in available documents [23]	Not specified in available documents	Not specified in available documents [23]	Not specified in available documents	• Not an open source • Commercial • Education version for classroom is available	Not specified in available documents

Models class	Sample of modelling tools & approaches	Temporal resolutions	Current temporal extent	Spatial resolutions	Current spatial extent	Open source	
						Model[3]	Solver
						• Free PowerFactory licences can be made available to students [21]	
	GridCal	Not specified in available documents	Not specified in available documents	Not specified in available documents	Not specified in available documents	Open source	Open source (a cross-platform power systems solver written in Python with user interface and embedded python console)
	PyPSA (Python for Power System Analysis)	Hourly	One year	National	Not specified in available documents	Yes, with additional open source software [57]	

Appendix C

Table C.6: Overview of some combined modelling efforts (detailed review within the text)

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. [24]
Irish TIMES (CE) + PLEXOS (PS)	To examine the suitability of features such as the system reliability and flexibility, renewable energy generation	One-way coupling: TIMES → PLEXOS • The main output information transferred from TIMES to PLEXOS:	• Finding: the work showed that in the absence of the detailed technical constraints of the power system model, there is an inconsistency in	• Limitation: the assumption that a future variable renewable energy supply portfolio can be represented by the historical data	Deane et al. [26]

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**
	curtailments, and CO2 emissions reduction calculated by Irish TIMES	electricity generation portfolio, fuel prices, and carbon prices	assessing flexibility and calculation of the CO2 emissions reductions		
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 [27]
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. [12]