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Energy modelling and the Nexus concept

Floor Brouwer [a, *], Georgios Avgerinopoulos [b], Dora Fazekas [c], Chrysi Laspidou [d], Jean-Francois Mercure [e], Hector Pollitt [c], Eunice Pereira Ramos [b], Mark Howells [b]

[a] Wageningen Research, PO Box 29703, 2502 LS The Hague, The Netherlands
[b] Division of Energy Systems Analysis, Royal Institute of Technology - KTH, Brinellvägen 68, 10044 Stockholm, Sweden
[c] Cambridge Econometrics, Covent Garden, Cambridge CB1 2HT, United Kingdom
[d] Civil Engineering Department, University of Thessaly, Pedeon Areos, 38334 Volos, Greece
[e] Radboud University, Faculty of Science, PO Box 9010, 6500 GL Nijmegen, The Netherlands

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ABSTRACT

The Nexus concept is the interconnection between the resources energy, water, food, land and climate. Such interconnections enable to address trade-offs and seek for synergies among them. Several policy areas (e.g. bio-based economy, circular economy) increasingly consider the Nexus concept. Ignoring synergies and trade-offs between energy and natural flows, can generate misleading modelling outcomes. Several modelling tools are available to address energy and the Nexus. Based on six such models, this paper aims to support the design and testing of coherent strategies for sustainable development. Model improvements would be achieved by comparing model outcomes and including a common baseline.

1. The Nexus of energy-water-food-land-climate

Energy, water, food, land and climate are essential resources of our natural environment, and support our quality of life. Competition between these resources is increasing globally, and is exacerbated by climate change. Continuing current trends in the use of natural resources means that people live beyond their boundaries (e.g. Ref. [1]). Improving resilience and securing resource availability would require improving resource efficiency.

The management of natural resources is interconnected and comprises a coherent system (also called the 'Nexus'). Interconnections between the Nexus sectors, e.g. energy and climate, often are bi-directional. Energy consumption, for example, has a direct effect on greenhouse gas emissions and subsequently impacts global climate. Moreover, climate change could have a direct effect on energy use as well: Total energy demand is foreseen to remain relatively stable, but energy demand for heating is decreasing and energy demand for cooling is increasing [2]. Renewable energy production in Northern Europe may benefit from climate change, but rising temperatures could increase severity of storms and impact conventional electricity generators [2].

Interconnections can often be subtle, thus might be ignored by policy makers and other relevant stakeholders. The Nexus concept acknowledges that putting pressure on one part of the Nexus can create pressures on others. Total energy consumption in the water sector currently exceeds 800 TW/h, and this is foreseen to increase by over 80% until 2040 [3]. Resource management in a Nexus-coherent manner is critical to securing the efficient use of our scarce resources. The Nexus is a concept to link energy with other natural resources. A proper understanding of how energy systems operate requires a good understanding of energy (including mining), engineering, hydrology, economics, food science, geography, social science and climatology.

A Nexus coherent analysis can lead to the design and planning of resilient systems and infrastructures. Even though the Nexus concept has only been established in earnest in this decade [4], it has already attracted the interest of researchers worldwide [5]. Behrens et al. [6] conduct a water-energy Nexus analysis to assess the vulnerability of electricity generation to water stress in the EU under climate change. They show that by 2030, 54 basins in the Mediterranean region and in France, Germany and Poland will

* Corresponding author.
E-mail address: floor.brouwer@wur.nl (F. Brouwer).

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experience reductions in power availability by thermoelectric power plants needing massive amounts of cooling water due to water stress. Despite these facts, further plants are actually being planned to be built in water-stressed basins.

The Stockholm Environment Institute (SEI) has developed two separate free-standing tools, the WEAP (Water Evaluation And Planning) and LEAP (Long-range Energy Alternatives Planning) systems. In recognition of the fact that water and energy systems are closely interlinked and water is needed in the vast majority of global energy production systems, while energy is essential for pumping, treating and distributing water, SEI has integrated WEAP and LEAP and they can exchange key model parameters and results and can together represent evolving conditions in both water and energy systems [7]. Both systems are used by hundreds of countries around the world and model water and energy demand and supply, their drivers and interlinkages, simulating real-world policies, priorities and preferences.

ETH Zurich and the Energy Science Center (ESC) have created the Integrated Energy Systems Modelling Platform (Nexus), enabling the study of complex questions about the impact of technical, socio-economic and political decisions on the performance of the future energy system [8]. The Nexus platform can be used for the needs and consequences of realizing the Energy Strategy 2050. The platform explores the role of flexibility providers in 2050, in light of the transition of the energy sector.

The Nexus concept differs from Integrated assessment and modelling (IAM). IAM combines the assessment of biophysical, natural resources and socio-economic dimensions of a system using modelling tools (e.g. Ref. [9]) with participatory involvement of actors at stake. Nexus modelling is different, since *interdisciplinary* approaches (including natural and social sciences) are combined with *transdisciplinary* research methods. Such transdisciplinary methods are key for knowledge partners working with end-users (policy makers and managers in charge of the Nexus components), SMEs and civil society organisations and using participatory approaches. In addition, the Nexus concept seeks to address trade-offs between these areas, and seeking for synergies among them.

The objective of the paper is to present the Nexus concept with a view to improve the capacity of energy modelling in Europe. The importance of the Nexus concept is presented in Section 2, focussing on the increasing cross-sectoral dimensions in European policy. This is followed by a brief overview of six key models used to support policy-making institutions (e.g. European Commission, Organisation for Economic Co-Operation and Development and the World Bank), presenting their existing capacity to cover energy and some of the other sectors of the Nexus. The paper concludes with follow-up steps to enhance the capacity in energy modelling to better address the Nexus concept and strengthen cross-sectoral policy support.

2. Why is the Nexus concept important for energy modelling?

[10] argue that a single water, energy, food sector approach is inadequate to provide basic water, food and energy services to the poorest on the planet. In addition, this will prevent society from adequately coping with climate change. The Bonn 2011 Nexus conference made an attempt to present early evidence of how a Nexus approach can ‘enhance water, energy and food security by increasing efficiency, reducing trade-offs, building synergies and improving governance across sectors’ [4].

Policy goals such as circular economy, low-carbon economy, resource efficiency, sustainable development, access to clean water and social welfare have been increasingly considering Nexus analyses in order to assess impacts and identify opportunities from a more holistic point of view [11]. The concept of bio-based economy explores the synergies between energy, water, food, land and climate with a strong focus on reducing, reusing and recycling of natural resources [12]. Moreover, the Sustainable Development Goals (SDGs) address the sustainable use of natural resources and a Nexus assessment would play a catalytic role in achieving them all simultaneously [10]. More specifically, the SDGs pertaining to the use of natural resources and consequently affected by a Nexus analysis are the following:

- SDG2 which aims at ending hunger, achieving food security and improved nutrition and promoting sustainable agriculture;
- SDG6 which aims at ensuring access to clean water and sanitation for all;
- SDG7 which aims that everyone has access to modern energy services which are reliable, affordable and produced in a sustainable manner; and
- SDG13 which aims at combating climate change and its impacts by taking urgent action.

Optimisation used in energy models gives insights into how to allocate energy resources in the optimal way, taking into account economic, natural, technical and political constraints [13]. Their outcome can then be adopted for decision support by policy makers. On the other hand, examining the energy sector in isolation can generate misleading results, especially given the synergies and trade-offs between energy and natural flows [14]. Therefore, the reliability and usefulness of the output of an energy model could be improved significantly if the following impacts are taken into account:

- Impact of change in precipitation levels on hydropower potential;
- Impact of cooling and operation of power plants on water resources;
- Impact of deployment of power plants (mainly renewables) as well as bioenergy crops on land availability;
- Impact of bioenergy crops on food production;
- Impact of energy use on climate change;
- Impact of water treatment and desalination on energy demand;
- Impact of food production on energy demand;
- Impact of climate change on atmospheric temperature and consequently on energy demand (heating and cooling).

When the above impacts are considered, energy modelling that supports sustainable policy making can increase its benefits significantly. Firstly, trade-offs (expected or unexpected) between various sectors can be identified both in current and future terms. Suggestions on cooperation across different regions can be made as a response to policies that look into the various problems in isolation and occasionally lead to conflicts. The quantification of those trade-offs and synergies between sectors can help optimize the benefits of a policy from an economic as well as a social point of view. Finally, progress in the achievement of the SDGs could be boosted as the interdependency between different sectors is examined.

The transition of the energy system towards lower carbon emissions following relevant and suitable “decarbonisation pathways” is a challenge to society, and matching energy demand with supply is increasingly dependent upon natural resources, which could be allocated for different purposes, leading to a potential scarcity (i.e. of water and land). An additional layer of complexity is added by the potential future impacts of climate change on all of these areas. Hence, energy models need to take the Nexus aspects into consideration in order to minimize the natural, social and economic risks.

3. Existing models addressing energy and the Nexus

The different components of the Nexus have their own specialised tools that are used for assessment. Integrated Assessment Models (IAMs) may be used to assess the interactions between the different Nexus components, allowing for the design of a much more coherent strategy for sustainable development.

We selected a number of well-known, existing knowledge models that provide detailed outputs for specific aspects of the Nexus, including energy. The set includes operational energy-climate-economic-water and land-use models, with most of them considering the interdependencies of only a few sectors and no single one is taking into account all five components of the Nexus.

The six models are selected to investigate their potential to improve support to energy policy. They are designed independently and with distinct purposes, using independent data sets, assumptions, and methodologies.

3.1. E3ME-FTT

E3ME (Energy-Environment-Economy Macro-Econometric model) is a macroeconomic simulation model that is based on post-Keynesian economic principles.[1] It is based on a set of macro-econometric behavioural equations (estimated over time series covering 1970–2015) that are fitted into the standard national accounting framework. The model thus has a strong empirical basis and solves annually out to 2050.

FTT (Future Technology Transformations) is an evolutionary model of technology diffusion, with sufficiently realistic features of consumers that enable the user to simulate the impact of detailed climate policies. It focuses on anticipating the effects of sustainability policies, by integrating behavioural and non-equilibrium complexity science and environmental feedbacks into the analysis [15]. E3ME is coupled to FTT models of the power and transport sectors, with additional models covering land, industry and households under development. Policies in the combined framework are assessed on the basis of their ability to effectively achieve certain objectives through the simultaneous use of several policy instruments that interact with one another. This approach is consistent with the one recommended by the European Commission in its Better Regulation guidelines [16].

Recent applications of E3ME include: inputs to the assessment of the EU's 'Winter Energy Package', the joint IEA/IRENA G20 report on expanding renewable energy[2] and an assessment of the economic and labour market effects of the EU's Energy Roadmap2050.[3] The full model manual [17] is available at the model website www.e3me.com.

3.2. MAGNET

MAGNET (Modular Applied General Equilibrium Model) is a global computable general equilibrium model with an additional focus on agriculture, it is a tool for analysis of trade, agricultural, climate and bioenergy policies. The MAGNET model has been used in the Agricultural Model Intercomparison and Improvement Project (AgMIP) [18], looking at long-term effects of projected climate change on agriculture [19] as well as the effect on food prices and land use of a significant increase in bio-energy as a climate mitigation option [20]. The macro-economic contributions of the emerging bio-economy are studied for the EU and The Netherlands by including detailed biofuels, bioenergy, biochemicals sectors and related policies within the model. MAGNET has been used to examine the interplay between the U.N. program to Reduce Emissions from Deforestation and Forest Degradation (REDD) and increased biofuel production from the Renewable Energy Directive (RED) [21]. MAGNET is coupled to the integrated assessment model IMAGE (see section 3.4), as its agro-economic component.

3.3. CAPRI

CAPRI (Common Agricultural Policy Regional Impact Analysis) is a global agro-economic model specifically designed for policy impact assessment of EU agricultural, trade and environmental policies. It is a global spatial partial equilibrium model, solved by sequential iteration between supply and market modules. CAPRI has been extensively used to assess agricultural policy measures, GHG emissions from the agricultural sector, food-water-energy linkages and climate change impacts [22].

Recent applications of CAPRI include: evaluation of the impacts of climate change on EU agriculture; evaluation of the livestock sector's contribution to the EU greenhouse gas emissions; assessment of the effects of EU biofuel policies; analysis of the effects of recent agricultural policy reforms (direct payments harmonisation, greening); assessment of agriculture-water relationships; Evaluation of the impact of recent Agricultural and Trade Policy Reform on Land Use. A sub-module enables to calculate the potential impact of climate change and water availability on agricultural production [23].

3.4. IMAGE

IMAGE (Integrated Model to Assess the Global Environment) is an integrated modelling framework of global environmental change, suited to large-scale and long-term assessments of the interactions in the society-biosphere-climate system. Core themes of the model are the effects of climate change, land-use changes, food and energy production in relation to human population growth and economic development. The agro-economic modelling in IMAGE is done via a coupling to MAGNET (Section 3.2). For representing vegetation dynamics, crop and grass production, Carbon and Water Cycles, IMAGE has incorporated the Lund-Potsdam-Jena managed Land (LPJmL) model (hard link, annual time step of data exchange) (Section 3.6). For assessing the impacts of global environmental change, IMAGE uses a range of additional models.

The model has been widely used for global environmental studies outlooks. Different pathways for energy, land use, greenhouse gas emissions and climate change are presented in Ref. [24].

3.5. OSeMOSYS

The Open Source energy Modelling System (OSeMOSYS) is a bottom-up optimisation modelling framework used primarily for long-term energy systems analysis and planning. The first code was made available to the public in 2008 and it has being further developed ever since. OSeMOSYS is built in modules in a way that allows for adaptations by the user [25]. Over the past years, it has been used to create sub-national [26], national, trans-national/continental [27] and global energy and integrated assessment (Climate, Land-use, Energy and Water) [28] models.

[1] Post-Keynesian models are demand-driven models, which are characterised by non-optimisation (full employment of resources is not a necessary result in Post-Keynesian models). Microeconomic theory in the Post-Keynesian tradition is based strongly in behavioural economics.

[2] http://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf.

[3] https://ec.europa.eu/energy/sites/ener/files/documents/2013_report_employment_effects_roadmap_2050.pdf.

3.6. MAgPIE -LPJmL

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a global land allocation model. Its objective function is to minimize total cost of production for a given amount of regional demand for food and bioenergy. It is coupled to the grid-based dynamic vegetation model LPJmL. Based on economic conditions, demand for agricultural commodities and food, technological development, land and water constraints, MAgPIE derives specific land use patterns, crop yields and total costs of agricultural production. The objective function of the land use model is to minimize total cost of production for a given amount of regional food and bioenergy demand [29]. It has contributed to the development of the SSP Scenarios: SSP Database (Shared Socioeconomic Pathways), the AgMIP project and to several World Bank reports.

4. Discussion: Comparative description of the models

As presented in Section 3, different models cover different nexus components, and while there is some overlap between the areas covered by different models, there is no single model that covers all nexus components.

The level of detail of the energy system in the models varies considerably. OSeMOSYS provides the highest level of detail and the FTT component of E3ME provides technological detail in the power and road transport sectors explicitly and directly, both for supply and demand. The other models have more of a focus on land use and the economy in the case of MAGNET, but have linkages to energy consumption through e.g. use of biofuels. Energy is only partly covered in CAPRI. The energy component of IMAGE includes 12 primary energy carriers in 26 world regions and is used to analyse long-term trends in energy demand and supply.

Looking into model differences with respect to the land-use component, it is event that models include land cover allocation, land use constraints, energy crop yields, and non-bioenergy land mitigation options. By linking energy, economy, climate and land use modules, it is also possible to calculate the direct competition of bioenergy with other energy technology options for greenhouse gas (GHG) mitigation, based on economic costs and GHG emissions from bioenergy production.

These differences mean that inputs from different models need to be used and linked in order to get the full picture of nexus policy domain interactions and impacts. The linking of models would partly resolve the problem of inconsistency between different model outputs and would offer a more cohesive story to the policy maker, even if it is only done at a very aggregate level. Results from one model (e.g. on Gross Domestic Product - GDP) can be fed through other models that use them as inputs, creating a more consistent story.

However, this approach raises several issues, from data harmonisation to interpreting and implementing a specific policy in the modelling framework, to potential contradictory model results. It seems that further integration of model results through other approaches, such as systems dynamics modelling, complexity science principles or fuzzy logic analysis to ensure that this linking is carried out successfully.

Some of the key challenges in using these models for policy support are presented in Table 1. For example, differences in geographical coverage raise practical difficulties in model linking, while combining optimisation and simulation approaches can

Table 1
Key features of models [39].

Model feature	E3ME-FTT	MAGNET	CAPRI	IMAGE	OSeMOSYS	MAGPIE-LPjML
Model type	Macroeconomic simulation model based on post-Keynesian economic principles	Global computable general equilibrium model with an additional focus on agriculture	Global agro-economic model	Comprehensive integrated modelling framework of global environmental change	Systems cost-optimisation model	Global land use allocation model, coupled to grid-based dynamic vegetation model
Main topics	Power, transport, land, industry and households under development	Trade, agriculture, climate bioenergy policies	EU agricultural, trade and environmental policies	Society-biosphere-climate system, climate change, land-use changes, food and energy production, biodiversity	land use, water availability and climate change	land use patterns, crop yields and total costs of agricultural production
Geographic coverage	Global with details on national level	Global with details on national level	Global with details on national level and sub-national for the EU	Global with details on sub-national level (grid-based)	National	Global with details on sub-national level (grid-based)
Energy dimension	Designed to handle interactions between the economy and the energy system. Its two-way linkages make it well placed to provide detailed analysis of the macroeconomic impacts of energy policy.	Allows for a quantitative analysis of the interaction between climate policies, energy sectors and the economy. Includes fossil fuels and various renewables (including among others bioelectricity, 2nd generation biofuels) as distinct economic sectors	Bioenergy, energy use in agriculture	Used to explore future mitigation pathways taking into account all relevant emissions and sources	Model primarily uses the energy sector as its entry point	Includes bioenergy production and competition for biophysical resources, full endogenous interaction between food, water and bioenergy as well as optimisation of resource use.
Nexus components	Energy, land, economy, climate	Food, land, economy, energy, climate	Food, water, bioenergy, environment, climate	Environment, biodiversity, land, water quantity and quality, energy	Energy, land, climate, water, materials	Food, land, water, bioenergy, environment, climate
Key gaps in addressing the Nexus	Food, water	Water	Competition in water and land between agriculture and non-agriculture	Food (via link with MAGNET)	–	–

make it very difficult to interpret results. However, in order to assess policies across the Nexus, some degree of model interlinkage is required.

Besides key model features, the underlying model philosophies need to be distinguished, in order to summarise whether the models focus on exploring the available policy space (optimisation models) or look at the impacts of specific policies (simulation models). In order to effectively inform policy-making, it is crucial to differentiate normative (i.e. “tell me what the components are and I will tell you the best way to organise the system”) from positive (i.e. “tell me the context and I will predict what people will choose”) modelling methods.

The normative models typically rely on a society minimising total costs or maximising aggregate utility and implicitly assuming a unique stable economic equilibrium [30]. These long-term outcomes help to understand the available policy space, but for policy makers can disregard critical aspects of reality such as unemployment and market disequilibria. For example, an economy in constant equilibrium, in permanent optimal state would not plan for or incentivise technological change – which may be the focus of sustainability policies.

It should be noted that the distinction of optimisation and simulation applies only to models that have a behavioural component; for purely natural systems models (e.g. climate or hydrological models), only a simulation approach makes sense. However, the situation can become somewhat confused by mainstream neoclassical economics, which relies on assumptions about optimising behaviour in order to link micro level decisions to the broader macro picture. However, the models that rely on equilibrium and optimisation principles miss the insights of behavioural science (now widely acknowledged in the work of [31]). More generally, it is acknowledged that the two different approaches are designed to answer different questions and using the wrong type of model could lead to misleading outcomes; a simulation model could never find the optimal outcome unless it assessed every single policy/technology combination, which is not possible in anything but the simplest model. Likewise, if an optimisation model is used in a simulation exercise then the behavioural assumptions it is based on become a feature of the results, suggesting unrealistic responses [15]. The issues are also discussed with a strong focus on technology development [32]. The links between micro and macro levels can also come under close scrutiny (e.g. Refs. [33,34] as the assumptions required to solve the optimisation routines in neoclassical models impose homogeneity on agents while the post-Keynesian macro-econometric models focus on the macro level only.

5. Conclusions: What does the Nexus imply for energy modelling?

Energy modelling would benefit from an approach that extends capabilities into other parts of the Nexus, but this would also require the careful design of the modelling concept, and use of well-accepted tools. There is also some crossover in model capabilities between the different tools available. These overlaps are not necessarily bad things, as they allow a comparison between different tools – giving insights into the importance of different assumptions or approaches and allowing some assessment of risk/uncertainty in the model outcomes. This approach of comparing model results is now standard in many policy applications in Europe (e.g. Ref. [16]).

The implications of the Nexus for energy modelling are listed below:

- First, to address interlinkages across sectors, overcome trade-offs and enhance synergies across energy and the Nexus sectors of water, food, land and climate. There is potential to improve energy modelling by better understanding the land markets, e.g. understand the potential for wind and solar energy. Interdisciplinary work across food science, engineering, hydrology is needed.
- Second, governance is essential in the Nexus, enabling to overcome trade-offs and/or enhance synergies between the Nexus sectors.
- Finally, transdisciplinary approaches allow to address the Nexus in a way it is driven by stakeholder needs [35]. Research would improve science-policy interaction, including participatory approaches, involving research, policy, business and civil society organisations.

Model improvements would be achieved by comparing model outcomes and develop a common baseline. Assessing integrated modelling frameworks applied on different scales is critical. The applicability of nexus analysis spans from neighbourhood scale [36] to national and international studies and from manufacturing processes (e.g. Ref. [37] to urban planning [38]). Further considerations of the Nexus in the context of energy modelling would enrich the modelling capacity and offer a basis for better policy advice. Coordination of work to enhance integration across multidisciplinary teams would enable to strengthen consistency of analysis across spatial scales.

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