Connecting Energy System Modelling with Sustainable Energy System Narratives at a Global Scale

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Abstract

This PhD thesis explores what can be considered a sustainable energy system on a global scale and what methods and tools can help sustainable energy policy design and assessment. Energy system modelling and sustainable energy system narratives are the two main areas of interest of this thesis. First current energy systems modelling practice was analyzed in the context of sustainable energy development, as well as how social science contributes to research focusing on sustainable energy. This revealed several main research gaps related to the topic of this thesis, including: (1) Most of existing energy system models have unrealistic or oversimplified assumptions that can negatively impact the quality of the models' outputs and consequently the quality of decision-making informed by such models; (2) There is a limited instrumental value of the available theories related to sustainable energy system development; (3) Current practice lacks global energy system narratives that would contribute a holistic understanding of the purpose and long-term goals of the energy system. Global energy system narratives would also contribute to the principles of sustainable design of the energy system. The remainder of the thesis became an attempt to close these identified research gaps in order to answer the main research questions. System dynamics, steady-state economics and energy justice theory are the main methodological and conceptual components of the thesis' research design. The contribution of the thesis includes: 1. A list of questions defining the current energy paradigm which can be used as a guidance for a sustainable energy system modelling; 2. A developed steady state of energy concept implying that energy sufficiency should be a universal energy system goal in the context of a long-term energy system sustainability; 3. A list of requirements for a socially sustainable energy provision based on energy justice principles. This list can be used as guideline for sustainable energy policy assessment and design; 4. A system dynamics model of electricity access provision in Sub-Saharan Africa. The model demonstrates an example of how energy system modelling: i) can be combined with sustainable energy system narratives for addressing methodological and disciplinary gaps in energy system research and ii) can contribute to better sustainable energy system policy design and assessment.

Key words: Sustainable energy system, energy system modelling, energy sufficiency, energy justice, system dynamics, energy transition, energy access, energy paradigm, global north, global south

L'abstrait

La thèse de doctorat explore ce que l'on a coutume d'appeler un système énergétique durable à l'échelle mondiale, ainsi que les méthodes et les outils qui peuvent aider à concevoir et à évaluer une politique énergétique durable. La modélisation des systèmes énergétiques et les récits (au sens de scénario narratif) de systèmes énergétiques durables sont les deux principaux domaines d'intérêt de cette thèse. Mon travail de recherche a consisté à explorer les pratiques actuelles de modélisation des systèmes énergétiques ainsi que la contribution des sciences sociales à la recherche en matière d'énergie renouvelable. Plusieurs limites ont été mis à jour : (1) La plupart des modèles de systèmes énergétiques existants reposent sur des hypothèses irréalistes ou simplifiées qui peuvent avoir une incidence négative sur la qualité des résultats des modèles et, par conséquent, sur la qualité de la prise de décision éclairée par ces modèles ; (2) les théories disponibles relatives au développement de systèmes énergétiques durables ont une valeur instrumentale limitée ; (3) il existe un manque au niveau des scénarios narratifs sur les systèmes énergétiques mondiaux, or ces derniers ont l'avantage d'offrir une compréhension globale des objectifs et des principes clés du système énergétique durable à long terme. Cette thèse se présente comme une tentative de combler ces lacunes de recherche à partir d'une réflexion méthodologique. La dynamique des systèmes, l'économie du Steady-State ou encore le champ de l'équité énergétique (Energy Justice) constituent les principales composantes méthodologiques et conceptuelles de la thèse. Les principaux résultats de mes recherches sont : (1) La liste des questions définissant le paradigme énergétique actuel qui peut servir de guide pour la modélisation d'un système énergétique durable ; (2) Le concept d'état d'équilibre énergétique développé impliquant que la suffisance énergétique (energy sufficiency) devrait être un objectif universel du système énergétique dans le contexte d'un système énergétique durable à long terme ; (3) La liste des exigences pour un approvisionnement énergétique durable sur le plan social, basé sur les principes d'équité énergétique qui peut servir de guide pour une évaluation et une conception des politiques énergétiques durables ; (4) Le modèle de dynamique des systèmes d'accès à l'électricité (energy access) en Afrique subsaharienne, qui montre comment la modélisation des systèmes énergétiques peut être combinée avec des scénarios narratifs de systèmes énergétiques durables.

Mots clés: Système énergétique durable, modélisation du système énergétique, suffisance énergétique, justice énergétique, dynamique du système, transition énergétique, accès à l'énergie, paradigme énergétique, Global North, Global South

Útdráttur

Í þessari ritgerð er rýnt hvað sjálfbær orkukerfi á heimsvísu fela í sér og hvaða aðferðafræði nýtist við hönnun á orkustefnu sem styður við sjálfbæra orkuþróun og hvernig meta skuli árangur aðgerða. Lögð er áhersla á líkanagerð og söguþræði (*e: narratives*) sem lýsa sjálfbærum orkukerfum. Fyrst voru núverandi líkön af orkukerfum og aðferðafræði við gerð þeirra metin í samhengi við sjálfbæra orkuþróun. Auk þess var hlutverk félagsvísinda í rannsóknum á sjálfbærri orku skoðað. Rýnin leiddi í ljós eyður í rannsóknum á sjálfbærum orkukerfum sem urðu rannsóknarefni þessarar doktorsritgerðar m.a.: (1) Forsendur flestra núverandi líkana af orkukerfum eru óraunhæfar eða of einfaldar. Þetta getur rýrt gæði greininga sem koma frá slíkum líkönum, og þau þar með styðja ekki jafnvel við ákvarðanatöku; (2) Það er takmarkað hagnýtt gildi af fyrirliggjandi kenningum um sjálfbæra þróun orkukerfa; (3) Núverandi aðferðir taka ekki til þróunar orkukerfa á heimsvísu sem myndi styðja við heildstæðan skilning á tilgangi og langtímamarkmiðum sjálfbærrar orkuþróunar. Aukinn skilningur á sjálfbærum orkukerfum á heimsvísu myndi einnig styðja við hönnun á sjálfbærari orkukerfum. Í þessari ritgerð var reynt að fylla upp í þessar eyður. Kvik kerfislíkön, jafnstöðu hagkerfi (e: steady state economics) og orkuréttlæti (e: energy justice) eru helstu kenningar og aðferðafræði sem er beitt í þessari rannsókn. Framlag rannsóknarinnar er m.a. 1. Spurningalisti sem skilgreinir hugmyndafræði sem hægt er að nýta sem leiðarvísi að líkanagerð af sjálfbærum orkukerfum; 2. Hugmyndafræði um jafnstöðu orkukerfi sem segir að grunnþarfir fyrir orku ætti að vera almennt markmið við uppbyggingu orkukerfa í samhengi sjálfbærrar þróunar; 3. Listi af forsendum fyrir þróun sjálfbærra orkukerfa byggt á kenningum um orkuréttlæti. Listann má nota sem leiðarvísi fyrir hönnun og mat á orkustefnu sem styður við sjálfbæra orkuþróun; 4. Kvikt kerfislíkan af aðgengi að rafmagni í þeim hluta Afríku sem er sunnan Sahara eyðimerkurinnar. Þetta líkan er dæmi um hvernig líkan af orkukerfum getur: i) verið samtvinnað hugmyndum um sjálfbæra orkuþróun og fyllt í eyður í aðferðafræði og rannsóknum á orkukerfum og ii) stutt við bætta stefnumótun og greiningum er varðar sjálfbær orkukerfi.

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List of Abbreviations

SDGs	Sustainable Development Goals
IAMs	Integrated Assessment Models
CLDs	Causal Loop Diagrams
SFDs	Stock and Flow Diagrams

List of Papers

Paper I: Chapter 2

Spittler, N., Gladkykh, G., Diemer, A., & Davidsdottir, B. (2019). Understanding the Current Energy Paradigm and Energy System Models for More Sustainable Energy System Development. Energies, 12(8), 1584. https://doi.org/10.3390/en12081584

Paper II: Chapter 3

Gladkykh, G., Spittler, N., Dierickx, F. (2017). Renewable energy – characteristics and representation in macroeconomic energy-climate models. Book chapter. European Union and Sustainable development: challenges and prospects.
https://www.researchgate.net/publication/320979533_European_Union_and_sustainable_development_challenges_and_prospects/link/5a05666b458515eddb857a8e/download

Paper III: Chapter 4

Diemer, A., Gladkykh, G., Spittler, N., Ndiaye, A., Collste, D., Dierickx, F. (2019). Integrated Assessment Models (IAM): How to integrate Energy, Climate and Economics? Submitted journal paper, under review.

Paper IV: Chapter 5

Gladkykh, G., Spittler, N., Davíðsdóttir, B., & Diemer, A. (2018). Steady state of energy: Feedbacks and leverages for promoting or preventing sustainable energy system development. Energy Policy, 120, 121–131. https://doi.org/10.1016/j.enpol.2018.04.070

Paper V: Chapter 6

Gladkykh, G., Diemer, A., Davíðsdóttir, B., (2020). Combining the socially sustainable energy system narrative with system dynamics modeling: A case of electricity sufficiency for Sub-Saharan Africa. Submitted paper to the Energy Research and Social Science Journal, under review.

Paper VI: Chapter 7

Gladkykh, G., Thazin Aung, M., Takama, T., Johnson, F.X., Fielding, M. (2020). Policy Dialogue on a Bioeconomy for Sustainable Development in Thailand. SEI Report. Stockholm Environment Institute: https://www.sei.org/wp-content/uploads/2020/01/200128a-mash-fielding-workshop-bioeconomy-thailand-pr-1912g.pdf

1. Introduction

A well-functioning energy system is a requirement for achieving social well-being. The way energy system is organized is interconnected with political, economic and social structures that exist in society. Today, the importance of having a sustainable energy system on a global scale is recognized internationally. One of the SDGs – SDG7 (Ensure access to affordable, reliable, sustainable and modern energy for all) – is dedicated to developing energy systems towards sustainability (United Nations, 2015). However, the question of what are the desirable and feasible ways of sustainable energy system organization globally and locally remains a challenging question at the political as well as research level.

Energy system includes all "all components related to the production, conversion, delivery, and use of energy" (Bruckner et al., 2014). Despite this straightforward definition, the boundaries of the energy system are constantly changing. With the improved understanding of how the energy system is embedded in the economic, social and environmental systems, energy system problems are no longer perceived as predominantly technological or an engineering challenge. Today, it is widely recognized that a transformative potential of the energy system is crucially dependent on the political decisions and social systems' change, not only on the technological advancement. Energy system challenges, such as lack of energy access provision in some regions and excessive energy consumption in others, unaffordable energy for consumers, environmental pollution, economic and political inequalities and dependencies embedded in the energy system structure (IPCC, 2014; IEA, 2018), are of a very high level of complexity. Solving them is associated with a wide range of research and decision-making challenges and requires interdisciplinary approaches and multi-directional efforts (Sovacool *et al.*, 2018; Xu *et al.*, 2016).

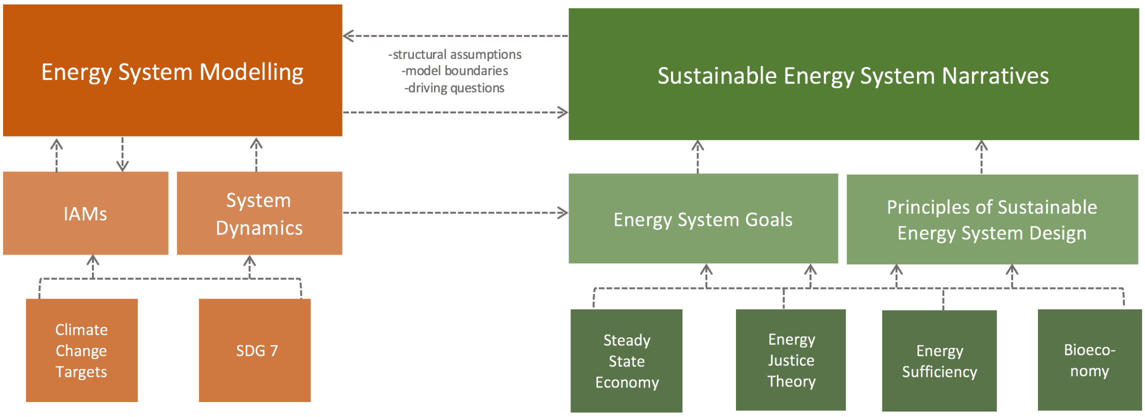
Research methods and tools used in energy system research are changing along with recognizing energy system's higher complexity. Today, two main trends in the energy literature are responding to this challenge. On the one hand, social science research in the energy field is advancing. During the last decade, in the energy literature, despite still dominated by engineering approaches, the number of studies related to the social science domain has increased significantly (Sovacool, 2014; Ramazan *et al.*, 2017). On the other hand, the field of energy systems modelling is advancing with energy system models gaining increasing attention as the tools for informing decision-making (Hitch et al., 1977; Evans and Hausfather, 2018)

This PhD thesis explores the energy system on a global scale. By connecting energy system modelling with the advancement of social sciences in energy research, the following overarching research questions are addressed: *What is the energy system on a global scale that can be considered sustainable?* and *What are the conceptual and modelling tools that can help sustainable energy policy design and assessment?*

1.1. Overview of the PhD thesis

Figure 1 provides an overview of the PhD thesis, which includes all the main structural components present in the six research papers comprising this thesis.

Fig. 1. *An overview of the PhD Thesis*



Energy system modelling and designing *sustainable energy system narratives* are the two main parts of this thesis. Each of them is associated with certain methods and concepts applied at different stages of the research process.

A part of this PhD thesis is dedicated to reviewing most widely used energy system models. Energy system models have gained a reputation of the useful supporting tools for better understanding of how energy system functions and for informing energy policy. The main motivation behind this part of the research was to understand to what extent existing modelling tools correspond to the energy policy and research agenda and whether the existing models incorporate in their structures already recognized interdisciplinary complexity of the energy system.

IAMs is a category of models that aim to understand complex interconnections between natural and socio-economic systems, play an important role in the energy and climate policy-making. In this thesis the role of IAMs is explored in the context of the current energy paradigm. Several IAMs are explored in this thesis in detail in order to better understand their underlying social dynamics structural assumptions.

System dynamics is a core methodological component of this thesis' research design and another building block of this thesis. System dynamics is based on systems thinking principles. It is an approach to understanding causal linkages, feedback loops, rates and levels and structural-behavioral relationships in the systems (Forrester, 1994; Sterman, 2000; Meadows and Wright, 2008). Ontologically, systems thinking is compatible with the principles of critical realism which incorporates the notion of systemic, holistic and causality a well as representation of the world based on the behavior-structure principles (Mingers, 2014). There are conceptual (CLDs) and quantitative System Dynamics modelling tools (SFDs) (Sterman, 2000). Both of these tools are used in different parts of this thesis.

Climate change targets and *SDG 7* (United Nations, 2015) are presented in Figure 1 to illustrate the main drivers setting the energy system modelling agenda.

The second thematic part of this PhD thesis (see Figure 1) is sustainable energy system narratives and focuses on exploring and developing sustainable energy system narratives. The narratives here are defined as elaborated theoretical visions of what an ideal sustainable energy system on a global scale could be. In contrast to the assumptions about the social realities discussed in the context of the energy system modelling, sustainable energy system narratives are not necessarily based on the currently existing social system structures. Sustainable energy system narratives can be based on the structural assumptions of a societal organization that are different from existing social constructs. *Energy system goals* (aimed at defining what needs to be achieved) and *principles of sustainable energy system design* (aimed at understanding how to achieve energy system goals) are the main components explored in this thesis in the context of the sustainable energy system narratives. These two components are in turn connected to the four conceptual building blocks that contribute to the development of a sustainable energy system narrative in this thesis. Daly's *steady state economy* acts as an inspiration and starting point for developing the concept of a socially sustainable energy system narrative. *Energy justice theory* (Jenkins *et al.*, 2016; Ramazan *et al.*, 2017; Biros *et al.*, 2018) and *energy sufficiency* act as fundamental components for designing the goals and the principles of sustainable energy system narrative. Energy justice is as a conceptual and a policy-making framework (Jenkins et al., 2017). The principles of the established energy justice discourse are grounded on environmental justice (Schlosberg, 2007) and climate justice literature (Shue, 2014).

Bioeconomy is only indirectly related to the sustainable energy system narrative part of this thesis. However, is represented in Figure 1 as one of the building blocks, because one of the papers in this thesis is specifically dedicated to exploring bioeconomy visions.

Overall, this thesis explores what sustainable energy system at the global scale is and how it can be achieved. On the theoretical level, this thesis, firstly, discusses sustainable energy system development by revealing dynamics and leverage points important to it. Secondly, it explores how sustainable energy system development has been addressed in energy systems models and compares the effectiveness of different modelling approaches for addressing different aspects of sustainable energy system development at different scales. Thirdly, it explores the concept of a sustainable energy system narrative and formulates a new, socially sustainable one, which includes socially sustainable goals and principles for sustainable energy system development. The results of the theoretical work are connected in this thesis to a practical modelling exercises, where it is explored how socially sustainable energy system narrative can be connected to the energy systems modelling and what are the policy implications associated with this. Finally, as a part of collaborative research, a study on exploring sustainable bioeconomy pathways is conducted which gives insights into understanding what sustainable economy narratives are and how sustainable energy narratives can fit in them.

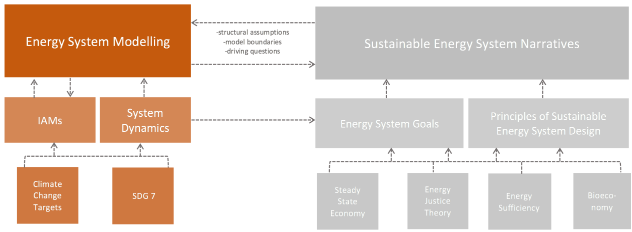
1.2. Summary of methods and results

In this section, a summary of each paper is presented, including research questions, methods and results.

Each paper addresses some of the PhD thesis components depending on the specific research questions. The navigation scheme provided for each paper helps to understand where a paper is placed in the thesis overview picture (see Figure 1).

1.2.1. Paper I[1]

***Fig. 2.** A navigation scheme for Paper I*



Spittler, N., Gladkykh, G., Diemer, A., & Davidsdottir, B. (2019). Understanding the Current Energy Paradigm and Energy System Models for More Sustainable Energy System Development. Energies, 12(8), 1584. https://doi.org/10.3390/en12081584

The main research questions of the paper are as follows:

- How can the current energy paradigm be defined?
- To what extent do existing modelling tools correspond to the energy policy agenda and how do they incorporate in their structures interdisciplinary complexity of the energy system?
- What kind of energy models are needed today to help answering the most important questions related to energy system development in light of the current energy paradigm?

This paper explores how different types of energy system models correspond to the overall sustainability agenda. The study provides a list of questions through which the current energy paradigm is defined. The concept of a current energy paradigm developed in this study follows the procedure of conceptual framework analysis (Jabareen, 2009) and builds on the latest research on sustainability relevant aspects of the energy system and international documents defining the international sustainable development agenda. This paradigm covers economic, environmental and social aspects related to energy system development. The questions formulated within the current energy paradigm derive from the following principles: (i) energy is essential for continuous socio-economic development and well-being; (ii) energy system development should not threaten any generations' quality of life and therefore it needs to stay within all environmental limits; (iii) resource limitations for fossil fuels and for renewable energies need to be accounted for.

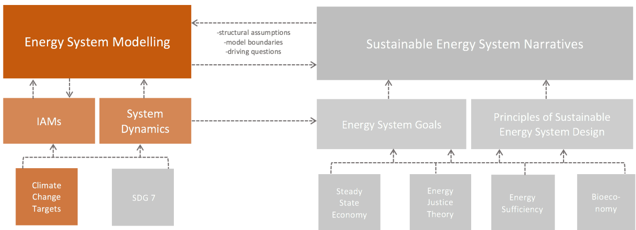
[1] Paper I resulted from a collaborative research. It was written in collaboration with Nathalie Spittler – a PhD colleague of Ganna Gladkykh. Both authors equally contributed to writing the text of the paper. The main role of Ganna Gladkykh was to define model categories based on the investigation of model reviews and carry out model analysis of top-down and other models. Nathalie Spittler was leading the part related to formulating the questions of the current energy paradigm and connecting them to the sustainable development agenda. Professors Arnaud Diemer and Brynhildur Daviðsdottir guided Ganna Gladkykh and Nathalie Spittler during the research activities and writing process.

The way the current energy paradigm is formulated predefines the most important components that need to be addressed in the current generation of energy system models.

A review of recent energy reviews covering a total of 55 models was carried out to assess how the current energy paradigm is addressed by energy system models. Following this initial review, 13 models were reviewed in detail. The study concludes that some critical assumptions about biophysical and social reality are missing in the majority of energy models and emphasize the importance of developing the new modelling approaches and tools. Acknowledging that each model serves a specific purpose and is not supposed to answer all the questions, the study provides a categorization of different types of energy models' (i.e. top-down, bottom-up and hybrid models) compatibility with each of the current energy paradigm research questions. This categorization can be used as a guidance for energy researchers and policy-makers that can help to understand a potential and the limits of different energy system modelling approaches.

1.2.2. Paper II[2]

Fig. 3. *A navigation scheme for Paper II*



Gladkykh, G., Spittler, N., Dierickx, F. (2017). Renewable energy – characteristics and representation in macroeconomic energy-climate models. Book chapter. European Union and Sustainable development: challenges and prospects.
https://www.researchgate.net/publication/320979533_European_Union_and_sustainable_development_challenges_and_prospects/link/5a05666b458515eddb857a8e/download

The main research questions of the paper are as follows:

- How are characteristics of renewable energy represented in macroeconomic energy-climate models?
- What are the gaps in modelling renewable energy in macroeconomic energy-climate models?

This paper explores how the definitions and assumptions made for various energy sources in macroeconomic energy-climate models affect the modelling results. Departing from a

[2] Paper II is a result of a collaborative research. The co-writers of Ganna Gladkykh is this paper are her PhD colleagues Nathalie Spittler and Florian Dierickx. Ganna Gladkykh main role was conducting the comparative analysis of the energy-climate models. Nathalie Spittler was responsible for writing a theoretical part related to the limits of renewables. Florian Dierickx was responsible for describing a political context of the energy-climate models use.

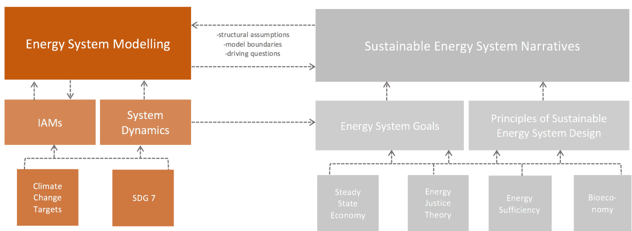
definition of renewable energy, the study discusses limitations associated with different types of renewable energy technologies. Deployment of renewable-energy-based technologies is associated with certain amount of the GHG emissions and non-renewable resources required for renewable energy harvesting (e.g. WWF, 2014; JRC, 2013). In this regard our analysis was focused on understanding whether the way renewable energies are modelled today allow for the feasible projections of renewable energy development. There are four comparative criteria for assessing the limitations of different renewables defined in the paper. They are as follows: (i) availability of unlimited primary energy source; (ii) need for critical materials for technologies required for harvesting renewable energy, (iii) impacts of climate change on availability of renewable energy source, (iv) emissions occurring energy production; during the conversion of primary to secondary energy. Based on these limitations, several renewable energy technologies are compared.

Discussion on the limitations of the renewables is followed by an overview of seven macroeconomic climate-energy models. This overview includes a description of the models' assumptions about renewable energy technologies and the connection between renewable energy and climate change. A special focus in the models' overview is put on the energy models used for energy scenarios and policies for the EU, focusing on PRIMES and GEM-E3.

It was discovered that in most energy-climate models, there are no connections between the stocks of renewable natural resources and renewable energy production. Acknowledging this limitation in the way renewables are modelled is very important, especially when it comes to interpreting climate mitigation scenarios resulted from the models' outputs. At the same time, better integration of the renewable energy limits in the models' structures can provide a good tool for supporting emerging research questions related, for example, to exploring what environmental and social injustices can emerge from the further development of the renewable energy system/infrastructure.

1.2.3. Paper III[3]

Fig. 4. *A navigation scheme for Paper III*



Diemer, A., Gladkykh, G., Spittler, N., Ndiaye, A., Collste, D., Dierickx, F. (2019). Integrated Assessment Models (IAM): How to integrate Energy, Climate and Economics? Integrated Assessment Models and Other Climate Policy Tools.

[3] Paper III is a result of a highly collaborative work lead by Professor Arnaud Diemer and lead-by-him project on analyzing IAMs. Ganna Gladkykh contributed to this paper by conducting full analysis of IMAGE and REMIND-R models and but contributing to developing the comparison framework for different models.

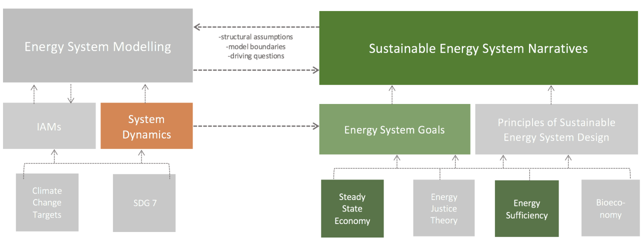
The main research questions of the paper are as follows:

- What are the main structural components, goals and assumptions of the IAMs policy drivers used to inform climate policy?
- What are the main problems associated with the current generation of IAMs?
- What are the main improvements of the IAMs that can be made to make the scenarios produced by IAMs more useful for informing climate policy-making?

Focusing on six (i.e. World3, DICE, IMAGE, MESSAGE, GEM-E3, REMIND) IAMs, this study compares the way climate-energy-economy nexus is addressed in those models. It is explored how the core modelling structures (including inter alia models' goals, macroeconomic assumptions, key variables) across different generations of IAMs have changed historically. Special attention is drawn to the fact to what extent the structures of different IAMs makes it possible to integrate such nexuses as population, agriculture, food production, biodiversity, water which are closely connected to the energy and climate and are crucial for ensuring sustainable development of societies. The comparative analysis of IAMs' structures is conducted with the use of CLDs. The analysis revealed that current generation of IAMs, due to advancement in research and increased capacities of the modelling tools, addresses a much higher level of climate-energy-economy complexity which allows exploring the trade-offs between environmental and economic policies in more detail. However, today's AIMs still contain a lot of gaps related to the ways biophysical and social complexity is presented in the models' structures. Limitations on the biophysical part mostly relate to the availability of data and the modelling effort needed. In contrast, addressing the gaps in the social system domain requires introducing new research methods and tools that can challenge established IAMs modelling practice (Gambhir et al., 2019).

1.2.4. Paper IV[4]

Fig. 5. *A navigation scheme for Paper IV*



[4] Paper IV was written in collaboration with Nathalie Spittler – a PhD colleague of Ganna Gladkykh, Professors Brynhildur Daviðsdottir and Arnaud Diemer. The main role of Ganna Gladkykh was to conceptualize the leverage points. Nathalie's Spittler role was to conceptualize sustainable energy system based on the Steady state economy theory. Both Ganna Gladkykh and Nathalie Spittler equally contributed to the writing of the text. Professors Arnaud Diemer, Brynhildur Daviðsdottir were guiding Ganna Gladkykh and Nathalie Spittler during the research activities and writing process.

Gladkykh, G., Spittler, N., Davíðsdóttir, B., & Diemer, A. (2018). Steady state of energy: Feedbacks and leverages for promoting or preventing sustainable energy system development. Energy Policy, 120, 121–131. https://doi.org/10.1016/j.enpol.2018.04.070

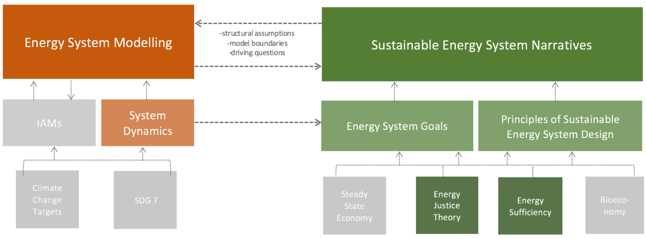
The research questions of this paper are as follows:

- To what extent can a steady state approach help conceptualize a sustainable energy system?
- What are the implications of using the steady state theory for a sustainable energy system at global and national policy levels?
- What policy leverages can be identified to achieve a sustainable energy system?
- How feasible is the goal of a long-term energy system growth for achieving sustainable energy?

In this paper, sustainable energy system narrative is explored from a biophysical perspective. Sustainable energy system is explored in a holistic manner aiming to understand underlying biophysical dynamics of the energy system development over time. In order to understand what constitutes a sustainable energy system, which stays within planetary as well as social boundaries, Daly's steady-state economy concept (Daly, 1974) is applied. In this study, Daly's equation of ultimate resource efficiency minimizing the service-throughput-ratio is transformed and extended into a detailed causal map of a steady-state energy system. As a result of this theoretical analysis, the Steady State of Energy concept is introduced. CLDs are used for conceptualizing and enabling a dynamic analysis of a steady-state energy system. It allows the depiction of the causal links and feedbacks among variables, from which the system's dynamics arise. In connection with Donella Meadow's Leverage Points (1997) approach, CLDs facilitated the identification of the implications of the steady state of energy for sustainable energy system development. Having conducted a conceptual analysis of the energy system leverage points, it was concluded that having sufficient amount of energy should be a long-term energy system goal on a global scale in order to achieve biophysically sustainable energy system. It is argued that energy sufficiency as the energy system goal is applicable in both the Global North and the Global South. The implication is that energy system expansion is needed in the regions with the lack of energy provision and, similarly, energy system contraction in required in those areas where the level of provided energy services is already beyond sufficient. In this way, energy sufficiency as the energy system goal is contrasted to the energy system growth. Defining energy sufficiency as the energy system goal within the Steady State of Energy concept resulted from the leverage point analysis. Using this framework, global energy policies are classified according to the level of their systemic impact. Transition to renewables as well as increasing energy efficiency, among other energy policies, which are on the top of the current energy policy agenda, are not ranked as high as energy sufficiency in terms of their potential policy impact. Based on the leverage points analysis, energy efficiency cannot continue increasing in the long term without depleting the stocks of natural energy resources, which is incompatible with biophysical sustainability and with the Steady State of Energy concept. The conceptual results of this paper indirectly contribute to the energy sufficiency versus energy efficiency discourse (Darby and Fawcett, 2018).

1.2.5. Paper V[5]

Fig. 6. *A navigation scheme for Paper V*



Gladkykh, G., Davíðsdóttir, B., Diemer, A., (2020). Combining the socially sustainable energy system narrative with system dynamics modeling: A case of electricity sufficiency for Sub-Saharan Africa. Submitted paper to the Energy Research and Social Science Journal, under review.

The research questions of this paper are as follows:

- What are the principles of socially sustainable energy system design on a global scale?
- What are the principles of energy access provision that can be considered socially sustainable?
- How can a combination of theoretical work with modelling help creating the tools for socially sustainable energy system policy assessment and design?
- What are the systemic implications of applying socially sustainable energy system narrative to the energy system modelling and energy system planning?

In this paper, the two main research threads of this thesis – energy system modelling and sustainable energy system narratives – are bridged (Fig. 1). Particularly, socially sustainable energy system narrative is connected to system dynamics modelling. In this way, it is demonstrated how methodologically energy system modelling and sustainable energy system narratives can be combined.

This paper builds on the results of Paper IV by exploring what socially sustainable energy system narrative is, departing from the idea that in the sustainable energy narratives research the social sustainability part is the least presented. This study departs from the argument that the way energy system goals are formulated in the SDG7 provides only fragmented understanding of the targets to be met in the future and does not contain a vision of a globally sustainable energy system. Taking all this into account, it is argued that without clearly formulated and agreed upon energy system goals, there is a risk that sustainable energy policies which have been designed and implemented are not be compatible with sustainability principles. Energy sufficiency defined though both a desired minimum and a desired maximum of energy consumption per capita is identified as a universal energy system goal within a socially sustainable energy system narrative. The second component comprising socially

[5] Ganna Gladkykh is the main author of the Paper V. Professors Brynhildur Daviðsdottir and Arnaud Diemer guided her work during the research activities and writing process and provided a lot of valuable inputs into the paper's content and form.

sustainable energy system narrative includes the principles of socially sustainable energy provision. These principles are defined based on the energy justice principles.

Energy justice (Jenkins *et al.*, 2016; Ramazan *et al.*, 2017; Biros *et al.*, 2018) is applied in this study as the main conceptual framework, being in the modern energy literature the best elaborated normative theory that brings social justice principles into energy system research. For the purpose of designing the principles of a socially sustainable energy provision, the three main energy justice pillars (i.e. procedural, distributional and recognition justice) (Jenkins et al., 2016) are operationalized. There are three overarching principles of a socially sustainable energy provision formulated in the paper: (i) energy provision solutions should prioritize basic needs of individuals and households above any other types of energy use; (ii) energy provision solutions should be compatible with the idea of contributing to building low energy society rather than high energy society; (iii) energy provision solutions should prevent creating power imbalances in the energy system at all levels. The designed principles are then applied for categorizing different types of and connected them to the several different types of energy provision technologies (i.e. decentralized renewables-based, decentralized fossil-fuel-based, centralized renewables-based, centralized fossil-fuel-based) to define the most and the least socially sustainable ways of energy access provision. It is concluded that decentralized energy access provision corresponds to more socially sustainable principles when compared to centralized energy access provision.

Apart from developing socially sustainable energy system narrative which contributes to the discourse of what sustainable energy system is, this paper demonstrates an example of how to design socially sustainable energy system narrative.

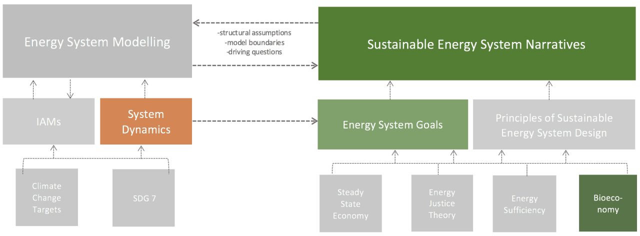
In this study, qualitative system dynamics approach is applied. A modelling exercise simulates the case of providing access to a sufficient amount of electricity for rural and urban households in Sub-Saharan Africa. This case is seen as a representative example of electricity access provision in the Global South. Socially sustainable energy system narrative and the system dynamics model are combined in the three ways: (1) at the level of conceptualizing the model's boundaries; (2) at the level of formulating the structural assumptions of the model's structure; (2) at the level of designing assumptions for the normative (socially sustainable) simulation scenarios.

At the stage of scenarios simulation, basic model scenario is compared with the two normative scenarios. The normative scenarios are designed around the principles of the socially sustainable energy access provision. In these scenarios, those types of energy provision technologies that do not correspond to the socially sustainable energy provision principles are excluded from electricity generation mixes. A comparison between the basic model run and the two normative scenarios allows to identify controversies and trade-offs between different technological choices for energy access provision. Particularly, the analysis shows that the most cost efficient technological mixes tend to be less socially sustainable and vice versa.

This study is a contribution to the interdisciplinary energy system literature. It demonstrates how conceptual sustainable energy system narratives can be connected to the energy system modelling and become more instrumental for a sustainable energy policy design and assessment.

1.2.6. Paper VI[6]

Fig. 7. *A navigation scheme for Paper VI*



Gladkykh, G., Thazin Aung, M., Takama, T, Johnson, F.X., Fielding, M. (2020). Policy Dialogue on a Bioeconomy for Sustainable Development in Thailand. SEI Report. Stockholm Environment Institute, Stockholm. https://www.sei.org/wp-content/uploads/2020/01/200128a-mash-fielding-workshop-bioeconomy-thailand-pr-1912g.pdf

The research questions of this paper are as follows:

- How is sustainable bioeconomy envisaged in different regions in the Global North and the Global South?
- How can stakeholder policy dialogues help to elicit sustainable bioeconomy visions and pathways in different regional contexts?

This paper resulted from Ganna Gladkykh research collaboration with Stockholm Environment Institute (SEI) within the Bioeconomy Policy Dialogues project. Bioeconomy is defined by SEI as the production, utilization and conservation of biological resources, including related knowledge, science, technology and innovation, to provide information, products, processes and services across all economic sectors aiming towards a sustainable economy. The project included developing the methodology for conducting series of stakeholder policy dialogues in different regions of the world and for analyzing their results. CLD mapping was used as a main tool for systematizing and comparing the results of the three stakeholder groups from Thailand participating in bioeconomy policy dialogues. As the result of the dialogues, three main sustainable bioeconomy pathways were discussed: agricultural pathway, biotechnological pathway, a pathways focusing on a social sustainability. The results of the dialogues analysis are compared to the three reference bioeconomy visions from the literature – a biotechnology vision, a bioresource vision, a bioecology vision (Bugge et al., 2016). The main conclusion drawn from this comparative analysis is that in the context of

[6] Ganna Gladkykh is the main author of Paper VI. She designed the methodology for comparative analysis of the dialogues and wrote the text of the paper. The rest of the authors participated in the workshops design and facilitation and assisted in data collection.
[7] Paper VI is a result of your stay at SEI as dictated by the ITN Marie Curie research grant.

Thailand social sustainability component is very strongly present even in biotechnology vision which is typically assumed in the literature to be the least focused on social wellbeing. The conclusion drawn from these results are that in the developing country's context social wellbeing and inclusiveness is prioritized even in the most technocratic sustainable bioeconomy visions prioritizing technological development above other societal transformations. Additionally, the results of the dialogues demonstrate a strong emphasis on the connections between the SDGs and sustainable bioeconomy.

This paper, even though it deviates from the energy systems research, provides a valuable contribution to understanding what are the existing alternative sustainable economy narratives. In this way, the study indirectly contributed to the discourse on how sustainable energy system narratives can be embedded in the sustainable economy narratives.

1.3. PhD thesis structure

The next six chapters of the PhD thesis (from chapter two to chapter seven) contain the six research papers which is then followed by a concluding discussion.

2. Paper I: Understanding the Current Energy Paradigm and Energy System Models for More Sustainable Energy System Development

energies

MDPI

Review

Understanding the Current Energy Paradigm and Energy System Models for More Sustainable Energy System Development

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Abstract: This study contributes to a better understanding of where to place different energy modelling tools and support better decision-making related to the sustainable development of energy systems. It is argued that through the connection of the energy field and the field of sustainable development, the current energy paradigm—encompassing economic, environmental and social aspects—has emerged. This paper provides an analysis of different categories of existing energy system models and their ability to provide answers to questions arising from the current energy paradigm formulated within this study. The current energy paradigm and the relevant questions were defined by conducting conceptual framework analysis. The overarching question of the current paradigm asks how different energy pathways impact on the (sustainable) development of the energy system and overall (sustainable) development globally and nationally. A review of energy system models was conducted to analyse what questions of the current energy paradigm are addressed by which models. The results show that most models address aspects of the current energy paradigm but often in a simplified way. To answer some of the questions of the current energy paradigm in more depth and to get novel insights on sustainable energy system development, it might be necessary use complementary methods in addition to traditional energy modelling methodological approaches.

Keywords: energy paradigm; sustainability; energy system models

1. Introduction

Energy has been at the centre of political and scientific debate for many centuries. In line with these debates, energy models representing energy systems have been developed. The energy system directly and indirectly interacts with economic, social and environmental systems. Through these interactions the systems influence the (sustainable) development of each other [1]. Energy is a central driver for economic and social development as well as environmental and climate issues. Today, with the emergence of the sustainability debate and considering the growing importance of the energy system in reaching multiple sustainable development goals, it is necessary to explore to what extent existing energy models are in accordance with the different aspects of the current views on the role of energy systems. In this paper these views are referred to as the current energy paradigm. No recent and comprehensive definition of the current energy paradigm exists, despite some earlier studies referring to an emerging or new energy paradigm [2,3]. While many energy model reviews exist (e.g., [4–7], so far none of them has been connected to the current energy paradigm. The aim of this study is to bridge this gap.

Energy modelling has a long history and often supports decision-making in energy system planning. The first simple linear programming energy models were developed in the 1960s. Since then, many more have been developed [6]. One category of energy models is that of energy system models. An energy system can be defined as the process chain (or a subset of it) from the extraction of primary energy to the use of final energy to supply services and goods [8]. In other words, an energy system encompasses the "combined processes of acquiring and using energy in a given society or economy" [9]. Therefore, in this study all models, which focus on energy production and usage in the system, including the society or the economy, are referred to as energy system models.

In aiming to understand what kind of energy models are needed today to help answer the most important questions related to energy system development in the light of the current energy paradigm and overall sustainable development in the context of the sustainable development goals (SDGs) [10,11]. This paper aims to develop two main points:

1. The formulation of the current energy paradigm and related questions.
2. Analysis of existing energy system models used for assessing and decision making in energy system development, specifically focusing on what models are able to answer which questions.

In order to help achieve sustainable development objectives energy models as supporting tools should be able to answer a variety of questions that go beyond purely technological advancement of energy systems [7]. This includes energy relevant aspects of the SDGs [12] and other biophysical and socio-economic ones (e.g., [13–17]). Hence, the practical implications of this paper are:

1. Support in choosing the most relevant model for investigating and understanding a particular issue.
2. Identifying gaps between the capabilities of existing energy models and requirements of the current energy paradigm facilitates improvement of existing energy system models.
3. Point one and two, individually or combined, can facilitate better application of models for decision-making related to the development of energy systems.

Section 2 describes the research method. In Section 3 the current energy paradigm is defined. In Section 4 the models are analysed. This includes a description of the model categories, examples for each of them and exploration of the question how the existing models relate to the current energy paradigm. This is followed by a discussion and critical reflection of the findings in Section 5. Finally, the conclusion presents a summary of the main findings in Section 6.

2. Method

To answer the question to what extent current energy system models are able to answer the questions of the current energy paradigm, a literature and model review was carried out. First, the relevant literature for defining the current energy paradigm and, second, selected models and their documentation were reviewed. The current energy paradigm is defined by following the procedure of the conceptual framework analysis presented in Reference [18]. This analysis is based on eight phases, which are carried out iteratively and among others includes mapping data sources, defining concepts and validation [18]. As suggested in Reference [18] selected data sources span a range of text types and disciplines including the following: for supporting the paradigm part, Kuhn's [19] theory of paradigms was applied. The definition of the new view on energy systems was derived from mainly two types of literature: (i) texts international documents dealing with energy in the context of sustainable development, such as UN reports and international meeting or session reports [10,20–31] (ii) studies on sustainability and energy relevant to the broader energy system, including literature from different disciplines on the resource, environmental, economic and social aspects of the energy system [3,6,13,15–17,32–55]. The concepts identified within the literature were categorized and later integrated [18]. This resulted in a number of core concepts, constituting the current energy paradigm. In this paper, the identified and integrated concepts are represented as questions that arise from the current energy paradigm (see Section 3 Theory—The current energy paradigm). This provides the basis for assessing what models are able to provide answers to which questions arising from the current energy paradigm.

To obtain information on energy (system) models, first an initial search for energy model reviews conducted within the last 15 years was carried out, which resulted in a total of thirteen energy model reviews that were explored. Following this, the model reviews were narrowed down to those that explicitly dealt with energy system models as defined in the introduction. This led to seven main reviews covering 55 models (i.e., [6,7,51,56–59]). These were used for gaining preliminary insights into the models and modelling practices of energy system modelling as defined above. Following the analysis of the reviews, a total of fourteen models were reviewed in more detail (see list below). Based on prior reviews [6,7,57,60] and the models' manuals, it was decided to categorize the models into top-down, bottom-up and hybrid models (more details in Section 4 Model analysis). Each of the categories encompasses several subcategories of modelling techniques (e.g., econometric, linear optimization).

Furthermore, due to the increased importance of energy in the field of sustainable development, energy plays a substantial role in models generally concerned with the assessment of sustainable development. Hence, it is considered important to, additionally to the energy system models, also include other assessment models that contain a substantial energy module. A total of seven (LEAP (the Long range Energy Alternatives Planning system) [61]; Threshold21 [62]; IMAGE (Integrated Model to Access Global Environment) [63]; FELIX (Functional Enviro-economic Linkages Integrated neXus) [64]; C-Roads [65]; DICE (Dynamic Integrated model of Climate and the Economy) [66]; REMIND (Regional Model for Investment and Development) [67]) of those models were reviewed.

The common features of each model group and the chosen models were investigated to identify how each of them addresses the questions raised by the current energy paradigm. In order to complement the general findings about the model groups, the results regarding the chosen models of each category are described in more detail. The exemplar models chosen for each category are distinct in their modelling characteristics and being representative for the different model categories. Additional criteria were the frequency of references to the energy systems models in the studied literature reviews and the policy relevance of these models. All of the chosen models are used in a policy-making context at a national, regional or international level. The models are:

Bottom-up

- MARKAL [68]
- TIMES [69]
- PRIMES [70]
- MESSAGE [71]
- WEM [72]

Top-down

- GEM-E3 [73]
- NEMS [74,75]

Hybrid

- MESSAGE-MACRO [76]
- MESSAGE-MAGICC [77]
- MESSAGE-Access [78]
- En-Roads [79,80]

Other assessment models

- LEAP [61]
- Threshold21 [62]
- IMAGE [63]
- REMIND [67]

3. The Current Energy Paradigm and Arising Questions

In the Oxford English dictionary a scientific paradigm is referred to as "a world view underlying the theories and methodology of a particular scientific subject." This relates to Kuhn [19] who defines it as a set of basic concepts and experimental practices of a scientific discipline. According to Kuhn, a paradigm is not necessarily explicitly formulated and can be implicit revealing itself through the assumptions shared by a disciplinary community. A central element of Kuhn's theory is that of a paradigm shift, which is defined as a process of changing from one set of concepts (assumptions) to another within a discipline.

There are three main questions that this section seeks to explore: (1) What is meant by energy paradigm? (2) Why has the energy paradigm changed? (3) How can the current energy paradigm be defined?

In this paper, the energy paradigm is defined as a set of explicit and implicit assumptions about the energy system. Whether or not energy studies can be related to a scientific discipline [81], Kuhn's theory of paradigm shift is applicable, if energy is seen as a field of study associated with a set of explicit and implicit assumptions. Despite Kuhn´s discussion of the paradigm shift mainly in the context of natural sciences, his concept has been used in many other contexts since his book was published, also in the energy field [2,82]. According to Kuhn, new knowledge and crises can drive paradigm change. The current energy system faces several challenges on the social and environmental sphere, which can be understood as crises as well as technological advancements and a new political agenda have been drivers of change [12,14,49,50]. Changes in fundamental assumptions about the energy system eventually define the way it is designed in reality. An energy system paradigm shift has occurred several times. The development of the current one is explained through to the emerging role of energy in the sustainable development debate and addressed challenges within theoretical research on energy [1].

To respond to the second question, a historical overview of the events and developments leading to the change of the energy paradigm is provided in Table 1. The relevant events, debates and corresponding literature for sustainable development (left column) and energy (right column) are displayed. In the middle column, the concepts derived from those two columns are presented. The concepts were obtained by conducting conceptual framework analysis (see Section 2 Method).

By integrating and synthesizing the concepts in Table 1 the answer to question number three (i.e., How can the current energy paradigm be defined?) is developed. The current energy paradigm can be described as the following: Energy is central for sustainable development and the goal of sustainable development, as defined in the Brundtland report, is central for the current energy paradigm. Three consequential aspects stem from this: (i) energy is essential for continuous socio-economic development and well-being; (ii) the facilitation of energy should not threaten any generations' quality of life and therefore it needs to stay within all environmental limits; possible future environmental impacts on the energy system need to be considered; and (iii) resource limitations for fossil fuels and for renewable energies need to be accounted for.

The main question arising from the current energy paradigm is "How do different energy system pathways impact (sustainable) development of the energy system and overall (sustainable) development globally and nationally?". The concepts presented in Table 1 translate into questions arising from the current energy paradigm presented in Table 2:

Table 1. Historical overview of the events and developments leading to the change of the energy paradigm and identified concepts (This table is based on a review of the following references: [3,6,10,13,15–17,20–55]).

Year	Sustainable Development	Concepts	Energy
1970s	Limits to Growth and WORLD3 model Conference of the Human Environment in Stockholm, Sweden	Limits of fossils and their implications Environmental impact Energy security	Oil crisis Hubbert curve Establishment of IEA Establishment of OPEC Energy Modelling Forum establishment
1980s	Brundtland report Creation of IPCC	Sustainable development	World Energy Council establishment Concept of the cost of conserved energy and energy supply curves
1990s	United Nations Conference on Environment and Development in Rio, Brazil Signing of UNFCCC Agenda 21 1st IPCC report	Climate change	Merge of energy and climate research Energy researchers contribution to Special report on Emission Scenarios Global Energy Perspectives book
2000s	MDGs 9th Session report of UN Commission of Sustainable Development World Summit on Sustainable Development Kyoto protocol Creation of EU ETS	Energy is central for sustainable development Link between energy and socio-economic development (incl. energy relation to poverty, urbanization, population dynamics) Cross-scale energy systems impacts (national/regional impact on global and vice versa)	IAEA, IEA, UNDESA, Eurostat and EEA indicator set World Energy Assessment - Energy and the Challenge of Sustainability by UNDP 1st EU energy action plan (20/20/20 targets)
2010s	SDGs Paris Agreement	Short-term versus long-term goals Synergies and trade-offs between different development goals Limits of renewables and their implications Impact of climate change on energy system	Launch of Sustainable Energy for All SDG 7 Critical material resource debate Climate change mitigation strategies Climate change adaptation strategies Climate and energy justice debate Deep Decarbonization Pathways Project

Table 2. Questions arising from the current energy paradigm.

Number	Question	Explanation
1	How does the energy system affect climate change?	This question refers to the effect the energy system, from production (including resource harvesting) to consumption, has on the climate. Hence, the model should provide greenhouse gas (GHG) emission values as well as their implications in terms of climate change effects (e.g., degree Celsius increases).
2	What other negative environmental impacts of the energy system exist?	This question refers to the pollutants that are not directly influencing the climate but have more local effects on the environment (e.g., water, land, air), for example, particulate matter, nitrogen oxides.
3	How does climate change affect the energy system?	This question refers to the potential feedbacks arising from climate change on the availability of renewable resources due to changed weather conditions (e.g., solar radiation, changed precipitation for hydropower).
4	What are the limits of fossil resource supplies and what are their implications?	This question refers to the scarcity and depletion of fossil fuels and how this influences the energy system in terms of availability and cost.
5	What are the limits of renewable resources and what are their implications?	This question refers to temporal availability of renewables and to scarcity of materials needed for harvesting technology and how this influences future renewable energy systems in terms of availability and cost.
6	How can a secure energy system be provided?	This question refers to the short- and long-term supply. Hence, it is addressing the availability of resources to meet the energy demand, considering the intermittencies for the short-term and potential resource scarcities in the long-term.
7	How does the energy system affect socio-economic development beyond GDP?	This question refers to the effects that the energy system has on human development, including its influence on health, affordability and poverty eradication.
8	How will near future energy system developments shape the long-term future energy system and how do long-term future goals impact on short-term developments?	This question refers to the fact that achieving certain goals in the near future can have impacts in the long-term and vice versa due to created path-dependencies and lock-ins.
9	What are the synergies and trade-offs between different energy system development goals?	This question refers to the fact that the energy system is interlinked with the social, environmental and economic system. Different goals with regards to each of the systems exist. Hence, it is important to understand how those goals relate to each other and whether they are conflicting or complimentary.
10	How does the development of the energy system of one country/region affect global development?	This refers to understanding whether the energy system development of a country/region can influence another country's/region's development (e.g., distribution of scarce resources, climate effects).
11	How do global developments affect the development of the energy system of a country/region?	This question refers to the influence globally negotiated goals (e.g., climate, energy, poverty eradication) might have on a country's/region's energy system development.

4. Model Analysis

Energy systems' structures represented in a number of existing energy models capture the assumptions about the energy systems they portray. Since the role of energy models is helping decision-making at different levels [57], it is important that the models can answer the questions resulting from the current energy paradigm. Thus, the modelling output can help feasible decision-making for energy systems' development.

The questions energy models aim to answer and the modelling tools have been constantly changing depending on the context of different historical periods and the thereby changing paradigm, advancement of knowledge and technologies. Hence, to explore to what extent the existing energy system models can answer the questions associated with the current energy paradigm defined in Part 3, the following aspects were analysed: (i) the methods used in energy models; (ii) the questions addressed in the models; (iii) the context in which the models were built. This will be discussed for every model (or family of models) within the three categories presented in the research design.

4.1. Bottom-Up Models

Bottom-up models aim to demonstrate the system's components in detail. In these models, structural elements are portrayed in a sophisticated manner using disaggregated data. Applying the bottom-up modelling approach to energy models means focusing on the technological complexity of the energy system. Bottom-up energy models normally ignore any interactions between the energy sector and other sectors of the economy. Hence, bottom-up models are also referred to as partial equilibrium models. For example, they seek for equilibrium in energy demand and energy supply. Bottom-up models are highly disaggregated. Therefore, due to data availability and complexity, it is hard to apply them to a large spatial scale (e.g., global). Such energy models are usually referred to as sophisticated engineering models and are based on simplified market behaviour assumptions, including rational behaviour of actors in the system [6,7,57,60].

Due to their equilibrium seeking nature, which often leads to modelling the energy system as an optimization problem (e.g., MARKAL, TIMES, MESSAGE), those models can in theory address questions related to resource limitations well. Constraints are put on available resources, which limits their availability and impacts on market prices. This is done for fossil resources for all the models that were analysed in more detail (i.e., MARKAL, MESSAGE, TIMES, PRIMES). No resource constraints regarding the critical materials for renewable resources are addressed in these models. However, some explicitly address constraints for biomass availability (i.e., MESSAGE & PRIMES). All of them consider intermittencies to some extent (e.g., capacity factors or time series) and have resource cost-supply curves for renewables. This means that those models, although in theory could provide answers to questions 4 and 5, only answer question 4 and partly address question 5 [71,83].

Climate change questions (i.e., questions 1 and 3) are partly addressed in bottom-up models but only in a linear manner, neglecting feedback between the components. The models are able to estimate greenhouse gas (GHG) emissions based on the energy mix and if certain policies are in place they can to constrain CO_2 emissions through price effects (e.g., CO_2 tax, CO_2 certificates). However, beyond this linear consideration of GHG-emissions, no feedback between the energy system and climate change is modelled in any of the models explored (i.e., MARKAL, MESSAGE, PRIMES, TIMES). Also, they usually do not consider any other environmental impacts associated with the energy system (i.e., question 2) [68,69,71,83].

As bottom-up energy system models are based on equilibria approaches. In these models, there is no feedback between climate change and the energy system and no possibility to model synergies and trade-offs between multiple energy system development goals. Such goals can include providing a sufficient amount of energy, minimizing environmental impacts and securing a stable long- and short-term energy supply. Thus, question 9 is not addressed by these types of models. However, this becomes possible with hybrid/nexus models (see Section 4.3 Hybrid models).

Regarding questions 10 and 11, models consider questions related to the impacts of global developments on national ones and vice versa, as MARKAL and TIMES can model energy systems at the local, regional and multinational levels. The MESSAGE model can represent the energy supply at national or global level. At the global level, MESSAGE aggregates the world into 11 regions.

Since bottom-up models are partial equilibrium ones, they only search for an optimal solution in the energy sector and do not address any aspects related to the overall socio-economic impacts of the energy system (i.e., question 7). However, one of the main focuses of some of the models in this group (e.g., MARKAL, TIMES, PRIMES) is energy system security. This means they answer question 6 within the boundaries of the assumptions on resource limitations. They do not fully account for the impacts of the limitations of renewables (i.e., question 5) on energy security.

It is argued that due to the technological innovation focus, bottom-up models can be applied for building long-term scenarios for the energy system but are not looking at the interaction between short- and long-term energy system developments (i.e., question 8) [60].

The characteristics presented above also reflect on how the models are used in decision-making. MARKAL and TIMES are used by numerous countries and organizations for energy planning at different geographical scales [68,69]. Both models belong to the linear programming-based optimization group using GAMS as a programming language. Their main objective is finding a combination of energy technologies ensuring energy security, energy affordability and reduction of CO_2 emissions at the lowest possible costs. MESSAGE is another widely used energy optimization model [71]. It is often employed for determining cost efficient technological portfolios allowing for GHG emissions reduction.

PRIMES is another technology-rich partial equilibrium energy model. It looks for an equilibrium solution for energy supply, demand, cross-border energy trade and emissions in European countries. It is used by the European Commission as energy policy decision support tool. However, unlike the aforementioned engineering models, some relationships between variables in PRIMES are based on econometrics. Thus, they are derived from empirics rather than solely relying on economic theory. With regards to the current energy paradigm, the main difference and strength of PRIMES is a detailed presentation of energy supply and energy demand sectors, as well as the mechanism of energy price formation. PRIMES incorporates a variety of policy instruments that can test the effects of different regimes and regulations on energy markets [83].

Contrary to bottom-up optimization models discussed above, the World Energy Model (WEM) is a bottom-up simulation model. The WEM is a large-scale simulation model which is used for energy policy projections. The model covers the entire global energy system, which is divided into 24 regions and includes several main modules: energy demand, power generation, refinery and transformation, fossil fuel supply, CO_2 emissions and investment [72].

In the WEM, the impact of the energy system on the climate is modelled in terms of emissions in both parts—energy supply and energy demand (question 1). No feedback from climate change to the energy system is present in the model (question 3). GHG emissions are modelled as the only environmental effect of the energy system (question 2). However, the model differs between GHGs (e.g., sulphur content). Resource limits for both fossil and renewable energy resources are integrated in the model in the form of dynamic cost-resource curves. Renewables are limited by regional resource capacities. No other limits for renewables, such as infrastructural materials, are available in the WEM assumptions (questions 4 and 5). Simulation of different sets of technological and investment solutions to secure region-by-region energy supply (including energy access provision for the regions undersupplied with energy) is one of the main focuses of energy scenarios produced (question 6). The World Energy Outlook 2017 [84] discusses the Sustainable Development Scenario produced by WEM, which includes three integrated sustainable development objectives corresponding to the goals of SDG 7 (affordable and clean energy), SDG 13 (climate action) and SDG 3 (good health and well-being). Exploration of trade-offs between achieving different development goals is part of the Sustainable Development Scenario (questions 7, 8, 9). Although the model's structure does not allow to assess country level effects, based on the available WEM documentation, it is difficult to say whether it is possible to identify trade-offs between regional and global energy system developments (questions 10, 11).

4.2. Top-Down Models

Top-down models aim to provide a bigger picture of the modelled system. Applying the top-down approach to energy system modelling usually implies that the energy system is part of a holistic economic system. This means that these models are focused on demonstrating interactions between different parts (sectors) of an economy rather than deeply analysing the systems' structural elements, such as energy technologies. They investigate how the energy sector interconnects with other sectors of the economy. They study overall macroeconomic performance and seek for a big systemic goal. Methods generally used for top-down energy models include macroeconomic and general economic equilibrium modelling based on econometrics. In this section, GEM-E3 and NEMS are discussed. NEMS can be classified as a modular hybrid model. It includes several supply and demand modules, combining technologically-detailed bottom-up modules with economic top-down ones [85]. However, in this paper, NEMS is classified as a top-down model. This is due to the fact that its modules are not used as individual models (see Section 4.3. on hybrids) and the model itself is widely used for macroeconomic projections, seeking to find general equilibrium across all sectors [86].

NEMS [74,75] is an economic and energy model developed by the Energy Information Administration of the US Department of Energy. The model seeks to understand the effects of alternative energy policies on the US economy by capturing the feedbacks between the energy sector and other sectors. One of the main focuses of the model is to investigate the interrelation between energy system development at the national and international level (i.e., questions 8, 10 and 11). Regarding energy resource scarcities (i.e., question 4), the only fossil fuel in NEMS for which natural resources depletion is explicitly addressed is shale gas [74].

Limits for renewable energy sources (i.e., question 5) in the model account for spatial and temporal resource availability. For solar energy, NEMS' assumptions acknowledge the dependency of solar technologies on natural resources but do not include it in the model's structure due to assumed abundance of those resources [87]. Climate change is not explicitly addressed in the model (i.e., questions 1 and 3). No sophisticated emissions sector is present but GHG emissions and other environmental pollutants (i.e., question 2) are included as a structural part of every economic sector, enabling tracking the impact of economic growth on emission targets. There are no socio-economic aspects beyond GDP, as well as the trade-offs between economic, social and environmental goals, addressed in NEMS (i.e., questions 7 and 9).

GEM-E3 [73] is a general equilibrium model which presents the world as a combination of 37 regions. It models the whole macro-economic system aggregated into 26 production sectors. As a general equilibrium model, GEM-E3 looks for simultaneous balance across all markets.

A large number of questions related to the current energy paradigm are addressed in GEM-E3. Question 1 is addressed by including a structure of energy system-caused emissions, which allows to track climate damage. However, the climate feedback to the energy system (question 3) is absent. Environmental impacts of the energy system beyond CO_2 emissions (question 2) are integrated into the model's structure. Apart from the possibility of better assessing environmental damages, this structure allows for a detailed analysis of climate change policies.

Limits for fossil fuels (question 4) are addressed but limits on renewable energies (question 5) are only included as exogenously defined constraints. One of the main focuses of GEM-E3 is energy security (question 6), which is represented by several indicators in the model. GEM-E3 addresses the energy system's impact on socio-economic development beyond GDP (question 7) by looking, in particular, at air quality and health impacts [88]. Being focused on exploring the role of the energy system in overall sustainable growth paths, GEM-E3 to some extent addresses the question of how the currently existing energy system shapes the future energy system (question 8). Trade-offs between development and environmental damages (question 9) are not explicitly addressed in the model but the mechanism of decision rules related to abatement cost and environmental damages are modelled in detail. Questions 10 and 11 are addressed in GEM-E3 and global as well as regional development dynamics can be tracked by, for example, exploring the changes in bilateral trade.

GEM-E3 is used by the European Commission as a decision support tool for tax, climate, energy, transport and employment policies. In particular, it was used for the EU 2030 Climate and Energy Framework and for the EU's preparation for the COP21 negotiations [73].

4.3. Hybrid Models

Top-down and bottom-up energy models are often contrasted as two extremes - "pessimistic economic paradigm" and "optimistic engineering paradigm" [89]. Hybrid models try to address the limitations of both types of models by connecting bottom-up and top-down approaches. Thereby, they combine technology-rich and macroeconomic model structures.

"The whole should exceed the sum of its parts: integrating aspects and functionality from top-down and bottom-up modelling approaches results in 'hybrid' models, which may provide more insight than the individual models could on their own" [90]. This is one of the latest definitions of this hybrid models. They are composed of fully working individual models and comprise two or more separate models, which can be integrated with each other to different extents. A common distinction of hybrid models is made depending on the extent to which the models are linked. They can be soft-linked (i.e., no integration of models, only external exchange of input or output data) or hard-linked (i.e., integration of models, including their structures and endogenous data exchange). The category of modelling systems, which combine multiple modules, is added to the classification of hybrids. However, in this paper, this category is not included in the hybrid section (see Section 4.2. Top-down models). [90]

Hybrid models can use more than one modelling technique. Those can include macroeconomic modelling, general economic equilibrium, linear optimization and partial equilibrium [7,60,91], as well as system dynamics.

Since hybrid models are not one coherent group of models but vary in their characteristics, it is difficult to generalize what questions related to the current energy paradigm are addressed by this model group and which ones are not. This depends on the models and indeed the techniques used to build the hybrid. Each of the hybrid models addresses a particular question, often relating different aspects of energy system development on different scales (e.g., the connection between large scale energy price developments and its impact on energy use and consumer health). Therefore, each model has certain strengths and weaknesses, as well as it makes it possible to address and answer different questions of the current energy paradigm. The following examples will illustrate the broad range of their scope.

MESSAGE-MACRO [76] is an energy partial equilibrium model connected to a general equilibrium macroeconomic model. The solution method of this model combines linear optimization for the MESSAGE module and non-linear optimization for the MACRO module. Inputs for the model are very detailed on the energy supply side (MESSAGE) and very aggregated for the energy demand side (MACRO). The main goal of this hybrid is examining the interrelations between energy supply costs as well as technologies and major macroeconomic parameters in order to provide the best short- and especially long-term policy. Hence, it is focused on addressing question 8 [76].

MESSAGE-MAGICC [77] is not a pure energy model but it is still seen as a relevant hybrid energy climate model. It is a hybrid that combines the bottom-up energy system structure with a more macro-level climate model structure. MESSAGE-MAGICC estimates the effects of the energy-use-caused GHG emissions on the global climate system; hence, its primary objective is providing answers to question 1. Outputs of this model, together with the other models, are used as inputs for assessments and scenario studies by the Intergovernmental Panel on Climate Change (IPCC), the World Energy Council (WEC) and other organizations. The MAGICC module represents the climate and is based on a global average energy balance equation integrating atmosphere and ocean climate dynamics [77].

MESSAGE-Access [78] also does not correspond to the commonly understood definition of a hybrid energy model and Access could be seen as a simple extension of MESSAGE. However, if a hybrid is broadly defined as two or more fully functioning individual models that produce more insightful results when combined [90], MESSAGE-Access can be counted as a hybrid. The Access module represents a choice of energy technologies in the residential sector. The output of MESSAGE-Access [78] looks at the consequences of a transition to clean cooking fuels and electricity in the poorest world regions and implications of this for the global energy supply. The model particularly looks at the costs of health, environmental and economic consequences of different energy transition pathways. Currently, MESSAGE-Access is used by the United Nations Secretary General's Sustainable Energy for All (SE4All) initiative aiming at meeting Goal 7 of the SDGs of clean and affordable energy [92]. By allowing for the assessment of access to modern energy and its related costs, in-house pollution and health implications of it, this model clearly addresses question 7 of the current energy paradigm. However, it still does not provide a full answer to this question, since the impact of the energy system on other related socio-economic indicators is not investigated (e.g., relation to poverty eradication). Furthermore, it looks at the connection between regional and global development, which relates to question 10 and 11 [78].

En-Roads [79,80] is a feedback-driven global scale system dynamics model. It explores interrelations between the energy and the climate system on an aggregated level focusing on some areas, which are represented in more detail (e.g., technology, innovation, price mechanisms). The model allows simulating different scenarios to explore how taxes, subsidies, economic growth, energy efficiency, technological innovation, carbon pricing, fuel mix and other factors affect global carbon emissions and temperature. Therefore, it is possible to investigate synergies and trade-offs between different policies, which explicitly addresses question 9. Another insight the model provides relates to understanding of how today's decisions on energy policy will affect the energy and climate system in the long-term (i.e., question 1 and 8) [79,80].

Together, all these models make it possible to say that hybrid models and their methods address most of the relevant questions of the current energy paradigm. However, it is obvious that although hybrid models often provide answers to many of the questions posed, no individual model can provide answers to all of the relevant questions. Nevertheless, it is expected that if energy system models do not answer all the questions related to the current energy paradigm, they should provide comprehensive assumptions and reasoning for not dealing with them (e.g., if some of the questions are beyond the scope or data is missing).

4.4. Energy in Other Assessment Models

This group of models contains models that cannot be qualified as energy models but are, nevertheless, of interest.

Four models were selected to be discussed in this section: Threshold 21 [62], LEAP [61], IMAGE [63] and REMIND [67]. The first two are system dynamics models. Neither Threshold 21 nor LEAP are energy models. In fact, they are macroeconomic models. They are considered relevant for the current discussion because, despite being focused on overall system sustainability rather than on the energy system only, they integrate a substantial energy component in their structures. This is strongly in line with the current energy paradigm, which sees energy as one of the main contributors to all pillars of sustainable development.

Threshold 21 [62] is a national, country level model. It integrates economic, social and environmental aspects. The model is used for designing and supporting long-term development planning in developing countries based on the SDGs priorities (question 7, question 9) [93]. The structure of Threshold 21 does not have an elaborated climate module but it includes a GHG emission module connected to the technological, energy and production sectors (i.e., question 1). No feedbacks between energy sector and climate change are modelled. The environmental impacts of pollution are present in Threshold 21 (i.e., question 2). However, the documentation of the model does not illustrate how detailed the environmental impact sector is. The limits for any fossil or renewable energy sources (i.e., questions 4 and 5) are not explicitly mentioned in the model's documentation. Threshold 21 is particularly focused on the trade-offs and controversies between achieving different SDGs, looking for the best national sustainable development paths. The most valuable insights from the model's simulation relate to identifying the best policy mixes for sustainable development by finding leverages for synergetic policy interventions for an integrated approach. Many of the leverages of this kind relate to energy system development. However, since Threshold 21 is not an energy system model, it does not answer specific energy-system-related questions. In particular, there are neither energy security aspects (i.e., question 6) nor short-term versus long-term energy system developments (i.e., question 8) explicitly addressed in the model's structure. In terms of policy impact, the model is widely used in developing countries as a tool for supporting sustainable development. Since the model has a strong national focus, it does not give insights on the connections between the national and international sustainable development (i.e., questions 10 and 11). In general, the structure of Threshold 21 is adaptable and customizable to a particular country's needs and priorities additional questions related to the current energy paradigm can be addressed.

LEAP [61] models energy production, consumption and associated GHG emissions in all main sectors of an economy. Its original design implies that the model combines different methods (e.g., optimization, partial equilibrium) and allows for the optional use of connected components (e.g., energy, water use, land use). LEAP has flexible data requirements and allows simulations with different types of output depending on the selected methodologies. The model supports running cost optimizing energy production and consumption scenarios, for which the OSeMOSYS (The Open Source Energy Modelling System) optimization model is used. Currently LEAP is used in more than 190 countries as a tool for integrated energy planning and greenhouse gas mitigation assessment (i.e., question 1), as well as a tool for energy assessments and Low Emission Development Strategies. Additionally, LEAP incorporates land use and water constraints with regards to renewable resources, which addresses question 5, as well as it is possible to model the impacts of the energy system on the environment beyond climate change (i.e., question 2) [61].

IMAGE [63] and REMIND [67] stand out from other models, because they belong to the model group called Integrated Assessment Models (IAMs). IAMs were initially intended to bring together the dynamics of natural and social systems in order to have better understanding of how human activities impact on natural systems, with particular emphasis on climate change [94]. They have played a major role in the scenarios developed in IPCC reports [95]. Most IAMs contain an energy system structure as the principle component, since it is one the main contributor to climate change. The current generation of IAMs contain relatively complex social system modules and aim at answering a wider range of questions related to sustainable development. Several IAMs exist developed and are used for assessing sustainable system pathways, including for example the Global Change Assessment Model (GCAM) (e.g., [96]), the Asian-Pacific Integrated Model (AIM) (e.g., [97]), the Emission Prediction and Policy Analysis Model (EPPA) (e.g., [98]) and others (e.g., [99,100]). For the purposes of this study, IMAGE and Remind were chosen as a representative models of the group.

IMAGE is a global/multiregional simulation model, which implies exploring the simulation of alternative scenarios of human and natural system development in the long run. IMAGE has a detailed emissions module, which accounts for the emissions to air, water and soil from the energy and the agricultural sector (i.e., questions 1 and 2). Climate change is modelled as temperature and precipitation changes, which feedback to water availability and land systems. Therefore, even though no direct feedbacks from climate change to the energy system are modelled, those feedbacks are indirectly available for hydro- and bioenergy (i.e., question 3). On the level of technological choice, no feedback from water scarcity to energy decisions is considered. Long-term fossil resource limits on the regional level are modelled as cost-supply curves (i.e., question 4). In a similar manner limits for renewable energy sources are modelled. The only exception is bioenergy, its production is limited by land availability and is connected to the agricultural land use (i.e., question 5). Energy security (i.e., question 6) is addressed in the model through resource depletion, energy resource trade and energy resource diversity. In its scenarios IMAGE explores possible impacts of climate policy on energy security. GDP is the main economic indicator but additional aspects relevant to human development are in the model, such as pollution impact on health and inequality in the form of GINI coefficient (i.e., question 7). IMAGE is positioned more suitable for exploring the long-term rather than short-term dynamics of it (i.e., question 8). As for the synergies and trade-offs between different development goals, the latest version of IMAGE is explicitly driven by questions related to reaching multiple SGDs and associated policy trade-offs (i.e., question 9). However, most of the insights related to those trade-offs are focused on the interrelations between energy and agricultural sectors. Among the evident trade-offs there are the ones related to land use, fertilizers, emissions, use of groundwater and their impact on prices, undernourishment and health. IMAGE is structured as a multiregional (26 regions) model. Therefore, it is possible to explore how changes in one region affect the development in other regions and where driving factors for major global changes are located geographically. However, there are limits for examining country-specific trends and policy changes, since most of the countries are modelled as part of the bigger regions (i.e., questions 10 and 11).

REMIND is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector [67]. The model's structure includes limits of non-renewable energy sources as well as potentials of renewable energies (i.e., questions 4 and 5). In addition to the primary energy resource limits, land use limits for energy system developments are taken into account. Dynamics of land use and agriculture are based on the MAgPIE [101] model. It is often coupled with REMIND to provide insights on the connection between the energy system and land use, which is especially relevant for bioenergy. The limits for the non-renewable energy resources are modelled in the form of the region-specific extraction cost-curves. Similarly, the limits for the renewable energies are modelled in REMIND as the maximum technical resource potentials in different regions. The feedback from climate change to energy resource availability is not modelled in REMIND (i.e., question 3). REMIND incorporates a sophisticated emissions sector which includes those of aerosols and ozone precursors (i.e., question 1). Also, additional land use CO_2 and agricultural non-CO_2 emissions are incorporated in the MAgPIE module. In addition to already mentioned environmental impacts considered a water sector is present in REMIND. It aims for accounting the water use associated with different energy technologies (i.e., question 2). The issue of energy security in terms of intermittencies of the renewable energy sources is addressed in the model structure in the form of a detailed energy storage sector (i.e., question 6). The social dimension and complexity of energy system development is not addressed in REMIND. Neither is socio-economic development beyond GDP, nor the trade-offs between energy system development and other development goals (i.e., question 7 and 9). Overall, social system projections are exogenous in REMIND and are based on SSPs [102]. Regarding the interplay between regional and global energy system dynamics, it is largely addressed by a detailed modelling of energy investment and trade (i.e., questions 10 and 11).

5. Discussion

The analysis shows questions addressed by different types of energy models. It is important to acknowledge that although a question might be addressed by some part of the model, it is not necessarily the case that the model provides a complete answer to the question (e.g., by including GHG emissions as an output parameter, it does not specify what the impact of the energy system's development on climate change dynamics is). Hence, many of the aspects are addressed but the extent to which the model answers the question needs to be considered more carefully. Table 2 provides an aggregated overview of the main strengths and weaknesses associated with different model types that have been derived from the literature and described in more detail above. Because models were built for different purposes it cannot be expected that one model all questions. Therefore, in the context of the current energy paradigm, it is important to understand what type of models are better at handling what questions and where there is room for improvement.

While Table 3 gives a general view on the strengths and weaknesses of particular model types related to answering the questions related to the current energy paradigm, it is important to provide a more detailed summary of the models' analysis results.

The first and second question of the current energy paradigm concerning climate change is addressed in many energy models of different types. However, the way it is integrated in the structures of most models is not aimed at addressing feedbacks and complex interrelations between the energy system and the climate. The climate sector in the energy models is often presented in the form of a GHG emissions-accounting units, demonstrating atmospheric GHG emissions and concentrations caused by different energy mixes. By modelling the climate sector this way, energy models do not aim to address the impact of the energy system on the environment. The main goal of addressing GHG emissions in energy models is cost optimization. Every ton of GHG emissions in such energy models is associated with monetary cost, which is taken into account when considering total cost of energy production and use. Thus, minimizing GHG emissions in such models is driven by the logic of minimizing costs from the supply and the demand side. This consequently leads to reducing negative impacts on the climate. From the modelling perspective, the presence of GHG-emission modules in energy system models makes it possible to connect them to climate models to arrive at more sophisticated assessment results.

As for the question referring to environmental impacts beyond climate change (i.e., question 2), it is mainly addressed by hybrid models. This is due to their different focus in general, which is exploring the effects between different systems. Other assessment models are especially concerned with this type of question as they are more explicitly addressing nexus questions and environmental issues such as the impact of pollution, land use and/or water. These issues are also often addressed by regional projects and research [103]. Due to the increasing interest of the policy and scientific field in understanding individual issues and especially the nexuses between food, water and energy, their relevance in energy system planning is growing [104,105]. Hence, their role in energy system modelling is gaining more relevance [48,106].

The questions concerning limits of natural resources (question 4 and 5) as defined by the current energy paradigm, which addresses the following two aspects: limits of fossil energy resources (e.g., oil, coal) and limits of renewable resources (i.e., needed for harvesting certain types of energy and resources themselves). The results show that it is common for energy models to address fossil energy resource scarcity. In fact, the question regarding fossil fuel limitations has already been asked in the past as part of the peak-oil debate [38,107] and therefore answers to it are presented in all types of energy system models. Limits for renewable energy resources are addressed rarely and mostly for bioenergy, which is a stock-based renewable energy source. Usually, limits for solar or wind energy are modelled considering spatial and temporal aspects of sun and wind availability. As for the limits of resources, such as scarce materials (e.g., Neodymium) and for harvesting flow-based renewable energy (i.e., solar and wind energy), there are no energy system models addressing them among those that were investigated. However, other assessment approaches, which rely on more biophysical concepts such as stock-flow modelling [108], the GEMBA (Global energy modelling—a biophysical approach) [109] EROI based calculations [110] consider those aspects. Question 6 is often addressed in relation to question 4, as long-term security of the energy system depends on the availability of resources. This is addressed for fossil fuels (question 4) in most models but not for renewables and materials needed to harvest them (question 5). With regards to the short-term security, which refers to the intermittencies, this is only addressed by limiting the allowed renewable capacity but is not assessed in more detail.

Table 3. Strengths and weaknesses of different model types.

Model Type	Strengths	Weaknesses
Bottom-up	• detailed and technology-rich structure allows to incorporate various resource constraints, cost implications of different technological developments and resulting emissions • national/regional modelling approach allows to assess interconnectedness between energy systems on country/regional/global level	• socio-economic aspects are addressed to a limited extent and the assumptions about socio-economic system are often simplified
Top-down	• broader scope makes it possible to examine feedbacks between the energy sector and other sectors of the economy • holistic approach for modelling economic system allows for climate change policies' analysis • socio-economic dynamics is modelled in relatively detailed manner	• simplified representation of the energy system makes it difficult to understand the implications of the different energy technologies' development
Hybrid models	• flexibility of the modelling approach allows to combine different models with different orientations in accordance with the research questions asked • it is possible to use models for different questions without changing model itself/developing new model • by combining bottom-up and top-down models the methodological limitations of both approaches can be reduced • the approach is suitable for modelling different nexuses related to energy system (i.e., water-energy, water-land-energy) • by combining bottom-up structures with macroeconomic structures models allow to examine policy-making in the short- and especially in the long-term	• the models' structures can be very complex, which may make interpretation of the modelling output difficult • connection of models of different scales and using different modelling techniques can be a time-consuming and high-technical-skills-demanding process
Other assessment models	• explicitly focused on overall system sustainability • design allows for exploring energy system contribution to the diverse aspects of sustainable development • explicit focus the trade-offs and synergies between achieving different SDGs • possible to model different nexuses relevant to energy system development • address a broad variety of environmental questions that allow to explore energy systems' impact beyond climate changes	• energy systems are modelled in a very simplified manner, which does not allow to answer specific energy-system-related questions
IAMs	• focus on exploring cost and benefits resulting from the interrelations between economic and climate systems make them best suited for analysing climate change mitigation and adaptation policies • approach allows for freedom in coupling different models and nexuses depending on research question needs • in many models the energy system structure is the principle component and is modelled in a detailed manner • new generation of models contain relatively complex social system modules and aim at answering a wider range of questions related to sustainable development	

The socio-economic aspect of the current energy paradigm is not addressed by bottom-up models as it is beyond their focus. It is mainly addressed by top-down and hybrid models. A more detailed review of models and tools that especially deal with rural electrification can be found in Reference [111]. Due to the nature of those aspects, socio-economic development factors, especially arising from rural electrification, are often dealt with in more detail on a smaller scale by qualitatively evaluating individual cases, for example [112] or analytically assessing and mapping the impacts of rural energy access and its effects [16,113,114]. However, the models often do not provide any answers concerning the socio-economic implications of the energy system beyond GDP. Hence, question 7 is only addressed and partly answered by few models.

It is possible to address the interrelation between long- and short-term developments when bottom-up and top-down models are connected, as each of them is focused on a different time scale (see Section 4.3 Hybrid models). Thereby, hybrids can provide answers to question 8. Question 9. The synergies and trade-offs between different energy system goals (e.g., energy access vs. environmental implications), is addressed and in some respects answered mostly by hybrid models, as their focus is on looking at different components of the energy system and relations between them. However, the example of WEM, which addresses questions 7, 8 and 9 in the Sustainable Development Scenario, demonstrates the potential that bottom-up simulation models have for exploring the trade-offs between different system goals.

Questions 10 and 11, regarding energy system development on different scales (local, regional, national, global), are mainly addressed through the aspect of trade and overall resource availabilities of fossil fuels. Trade of different energy sources defines supply and demand dynamics, through this price is affected. Potentially, trade of resources needed for harvesting energy could also be included in the energy models' structures, influencing prices for different energy sources. However, as was mentioned before, natural resources needed for harvesting energy are not addressed in the investigated energy models at all.

The current paradigm as defined here will evolve and change over time. Due to the importance of energy and its role for sustainable development, as also shown by the multiple links of SDG 7 to the other SDGs, it is likely that this will continue to shape the energy paradigm [11]. This would imply more widespread calls for holistic analysis of energy systems, making multi-dimensional analysis the rule rather than the exception.

The main limits of this study arise from its research design, which implied analysing model categories and only a number of models as representative examples within each modelling category, rather than discussing a large number of individual models in detail. Lopion et al. for example analysed models with regards to their strengths and weaknesses focusing on environmental and technical aspects of models. However, in their analysis they did not encompass all aspects of the current energy paradigm [5]. Thus, future research may analyse an extended number of energy system and integrated assessment models in terms of their correspondence to the current energy paradigm.

6. Conclusions

The aim was to understand what kind of energy models are needed today to help answer the most important questions related to energy system development in light of the current energy paradigm and thereby, facilitate more sustainable (energy) system planning and development. This study, first, formulated the current energy paradigm and the questions arising from it. Second, the study analysed to what extent those questions are answered by current energy system models.

The current energy paradigm, as formulated in this study, arises from the link between energy and sustainable development. Thus, energy models that serve the purpose of helping decision-making in designing energy systems for sustainable development, should be able to answer the questions arising from this paradigm and the relevant questions for specific purposes.

Understandably, it was found that none of the models chosen to be analysed can answer all of the questions related to the current energy paradigm, because they were built for different purposes.

However, most of the questions are to a bigger or lesser extent addressed by at least one of the energy models explored. Therefore, it is necessary to choose the right model for relevant questions in a specific context.

It was often difficult to make a clear distinction on whether or not a particular model answers or addresses the questions posed. However, there is clear evidence of aspects of the current energy paradigm that are most and least represented by existing energy models. Regardless of the scale or method of modelling applied, the natural systems' interrelation with the energy system is addressed in most of the models as well as fossil fuels resource limits and energy-system-caused GHG emissions. In contrast, the limits for renewable energy as well as the feedbacks from the climate to energy systems are not present. The reason for exclusion of these aspects may be caused by a high level of uncertainty of potential environmental and cost impacts.

The question of trade-offs and synergies between different energy systems goals (i.e., social, economic, environmental), which is especially important in the context of understanding the role of energy systems in sustainability pathways, is not explicitly addressed by energy models currently used for policy making. Still, there are models of a new generation that explicitly look at such sustainable development trade-offs and synergies. Those models, in spite of presenting the energy sector in a simplified manner, can bring interesting insights to the role of the energy system in sustainable development and can support the design of sustainable energy pathways.

Overall, this analysis showed that in order to better understand how to improve energy modelling tools and support better decision-making related to the sustainable development of energy systems, models need to be approached critically. Even though most models address aspects of the current energy paradigm, they might do so in a simplified way. It is necessary to reflect on the questions needed to be answered and in what way the model can help answer them. It is believed that in order to answer some of the questions of the current energy paradigm in more depth, it might be necessary to depart from traditional methodological approaches and ways of thinking and use complementary methods. It can be argued that discussion on it is relevant to a community of energy researchers and practitioners, including energy modelers and policy-makers as it influences their work.

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Acronyms and Abbreviations

C-Roads	Climate Simulation Model
CO_2	Carbon dioxide
DDPP	Deep Decarbonization Pathways Project
DICE	Dynamic Integrated model of Climate and the Economy
EEA	European Environment Agency
En-Roads	Energy Simulation Model
EROI	Energy Return on Investment
EU ETS	European Union Emission Trading System
EU	European Union
Eurostat	European Statistics
FELIX	Functional Enviro-economic Linkages Integrated neXus
GAMS	General Algebraic Modelling System
GDP	Gross Domestic Product
GEM-E3	General Equilibrium Modelling for Energy-Economy-Environment
GEMBA	Global Energy Modelling—a Biophysical Approach
GHG	Greenhouse Gas

GINI	Measure of statistical dispersion to represent income/wealth distribution
IAEA	International Atomic Energy Agency
IAM	Integrated Assessment Model
IEA	International Energy Agency
IMAGE	Integrated Model to Access Global Environment
IPCC	International Panel on Climate Change
LEAP	Long range Energy Alternatives Planning system
MAgPIE	Model of Agriculture Production and its Impact on the Environment
MARKAL	Market Allocation
MDGs	Millennium Development Goals
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental impact
MESSAGE-Access	MESSAGE Energy Access Model
MESSAGE-MACRO	MESSAGE Macroeconomic Model
MESSAGE-MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
NEMS	National Energy Modelling System
OPEC	Organization of the Petroleum Exporting Countries
OSeMOSYS	The Open Source Energy Modelling System
PRIMES	A computable price-driven equilibrium model of the energy system and markets for Europe
REMIND	Regional Model for Investment and Development
SDGs	Sustainable Development Goals (SDGs)
SE4All	Sustainable Energy for All
SSPs	Shared Socio-Economic Pathways Scenarios
TIMES	Integrated MARKAL-EFOM system
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
UNFCCC	United Nations Framework Convention on Climate Change
WEC	World Energy Council
WEM	World Energy Model

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3. Paper II: Renewable Energy – Characteristics And Representation in Macroeconomic Energy-Climate Models. Book chapter. European Union and Sustainable development: challenges and prospects

Renewable Energy – Characteristics and representation in macroeconomic energy-climate models

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The current energy system, which is fossil-fuel-based, has been identified as one of the main drivers of earth system change. Although impacts of human beings are observable even earlier, none of the changes before (e.g. change in the agricultural system) caused such a significant impact on the environment as the one of the energy system (Steffen et al., 2005). Hence, it is no surprise that the energy system is also modeled as a main driver for climate change in many macroeconomic energy-climate models. One of the suggested solutions to climate change mitigation is a transition from a fossil-fuel-based energy system to a renewable-energy-based one (Edenhofer, Pichs Madruga, & Sokona, 2012; Iiasa, 2012; International Energy Agency, 2014). In the IPCC's report, renewable energy is defined as "*any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. Renewable energy is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes low-carbon technologies such as solar energy, hydropower, wind, tide and waves and ocean thermal energy, as well as renewable fuels such as biomass*" (Edenhofer et al., 2012, p. 38). It is assumed by the authors that the definitions and assumptions made for various energy sources in macroeconomic energy-climate models are affecting the modelling results depending on how the relations between climate change and the energy system are analysed. Characteristics chosen to be considered when modelling renewable energy technologies can influence modelling results. Hence, the paper deals with the following research question: How are characteristics of renewable energy represented in macroeconomic energy-climate models? To answer this question we start from the above-mentioned definition of renewable energy. Then, in a disaggregated manner, we analyse characteristics of different renewable energy technologies, relevant for the interaction between climate change and the energy system. This is followed by an overview of several macroeconomic climate-energy models including a description of their assumptions about renewable energies and a description of the connection between renewable energy and climate change. Based on the former, the differences of definitions and theories of renewables, as well as their representation in models, are discussed. A special focus will be put on the energy models used for energy scenarios and policies for the European Union (EU) PRIMES and GEM-E3.

Characteristics of renewable energies

There is no uniform definition of renewable energy. Other ways, than the above mentioned definition of renewable energy by the IPCC can be found in the literature. Some of the definitions are broad but others give a more detailed description of renewable energy or a subset of it. However, most commonly a definition of renewables similar to the one of renewable energy by the IPCC is provided. An example of this is the definition of the German Advisory Council on Global Change: "*These include the energy of the sun, water, wind, tides, modern biomass and geothermal energy. Their overall potential is in principle unlimited or renewable, and is CO2-free or -neutral*"(German Advisory Council on Global Change, 2003, p. 236). Furthermore, a definition of renewables can be distinguished between different types of renewables. The German Advisory Council on Global Change recognizes "*new renewables*" specifically, which are those that have only recently been discovered, developed and employed and therefore still bear great potential; this, for example, excludes hydropower. Another possible distinction is between combustible and non-combustible renewables. Every renewable energy source, apart from bioenergy can be considered non-combustible (Vera, Langlois, 2007). Those definitions despite not giving any more detail provide insights into the fact that renewables only in principle have unlimited renewable potential, as well as the categorizations suggest that different renewables have varying characteristics and environmental impacts. Some of these renewables cannot be seen to be 100% renewable despite the fact that the source might be constantly renewable. For example, the technology for harvesting the source might depend on scarce or critical resources (WWF 2014) and constrain the possibility to harvest a specific renewable resource at a certain point in time. Even if the energy source itself might be renewable, resource constraints with regards to harvesting it might exist and must be considered. This is in line with Garcia-Olivares argument that a future energy source "*must not depend on the exploitation and use of scarce materials*" (García-Olivares, Ballabrera-Poy, García-Ladona, Turiel, 2012).

By not including the arising constraints for renewables in macroeconomic energy-climate models, renewable energy might be represented in a way that allows for misleading conclusions based on modelling results. Table 1 displays renewable energy technologies, which from today's perspective are considered technologically and economically feasible and are commonly referred to as alternative, that can help to combat climate change (Edenhofer, Pichs Madruga, Sokona, 2012; Iiasa, 2012; International Energy Agency, 2014). Additionally, the potential of renewables in a certain location can also be impacted by climate change. Hence, this is another component that is vital for modelling renewables in macroeconomic energy-climate models, as not only the energy system impacts on climate change but also the other way around (Schaeffer et al., 2012).

Based on the above, the categories to characterize each of the renewable technologies were chosen for the following reason:

(i) Unlimited energy source: This refers to the primary energy source (e.g. sun). Due to the rate of harvesting (if the rate of harvesting exceeds the sustainable harvesting rate), some resources that are considered renewable might become non-renewable (e.g. geothermal).

(ii) Critical materials for harvesting technology: A renewable resource is only 100% renewable if harvesting does not depend on any critical or scarce resources.

(iii) Impact of climate change on energy source: Climate change itself can impact on the availability of a certain energy source and its harvesting potential. For example, does climate change heavily impact on water resources and therefore on the water available for energy generation (de Queiroz et al. 2016).

(iv) Emissions during energy production processes: These emissions refer to those occurring during the conversion of primary energy to secondary and final energy. Not all renewables are CO2-neutral or -free, to a large extent this can depend on their harvesting rate.

Table 1: Disaggregated analysis of renewable energy technologies

Technology	*Unlimited source*	*Critical materials for harvesting technology*	*Impacts of Climate Change on source*	*Emissions during energy production*
Solar PV	yes - sun	Copper, Gallium, Germanium, Indium, Selenium, Silver, Tellurium, Tin	yes	no
Solar Cells	yes - sun	-	yes	no
Concentrated Solar	yes - sun	Copper	yes	no
Hydropower Small	yes - water	-	yes	no
Hydropower Large	yes - water	-	yes	no
Geothermal	possible - earth		no	yes
Biofuels	possible - biomass	-	yes	yes
Biomass solid	possible - biomass	-	yes	yes
Wind	yes - wind	Cobalt, Copper, Manganese, Molybdenum, Nickel, Rare Earths	yes	no

Each of the above-mentioned characteristics has an implication for integrating renewables into macroeconomic energy-climate models. According to the definition of renewable energy given by the IPCC, the energy can be classified as renewable only if its harvesting rate is below the recovery rate. This is especially relevant for biomass but also for geothermal energy. With regards to critical materials for the existing harvesting solutions, especially those technologies currently receiving a lot of attention (PV, solar and wind) require a number critical and potentially scarce materials. Almost all technologies require copper (including hydropower and geothermal). However, a study by the WWF (2014) found that only the copper use of PV, wind and concentrated solar power had a significant impact on its availability. Although emissions from biofuels and solid biomass (if harvested sustainably) do not cause net emissions, there still occur emissions during the combustion of biofuels. The emissions arising at geothermal plant sites vary for different sites. The availability of all renewable energy sources, apart from geothermal, at a certain location at a certain point in time can be influenced by climate change. Those impacts vary according to the specificities of the region (e.g. change of solar radiation intensity; change in composition of crop availability due to temperature changes; less energy density in water flow due to lower precipitation) but should be considered when modelling the possible contribution of renewable energy to combating climate change on a regional and/or global scale.

In Table 1 only the interaction between renewable energy and its impacts on climate change were assessed, other environmental impacts were not taken into account. However, some of the carbon-neutral renewable energies (e.g. hydropower) do not affect climate but interfere with the proximate ecosystem, which might also lead to negative impacts on the climate in the long run. This means that even if a source is renewable it might not be fully sustainable. Other aspects that need to be considered when talking about sustainable energy are the following: spatial dependence due to environmental circumstances, resource competition with other sectors (e.g. food, transport) and global security issues. Environmental implications of building renewable energy infrastructure is another important issue. Table 1 does not take into account critical materials and emissions associated with building additional distributional infrastructure for different types of renewable energy. In case energy-climate models provide for the possibility of building up renewable energy capacities, environmental implications of such activities should be included in the models' assumptions.

Modelling renewables in the context of climate change, societal values, territory, energy security

Biophysical aspect of renewable energy, including natural resource use and emissions, is a crucial but not the only dimension which needs to be addressed when building macroeconomic energy-climate models and designing scenarios for renewable energy development. The authors believe that the issues such as geopolitical interests and financial flows are of crucial importance in renewable energy models. Modelling practice is always driven by underlying assumptions based on cultural, personal and societal values and broader regional or national geopolitical interests. However, the opposite is also true - regional or national strategies and the political climate with regards to environmental issues might be influenced by modelling results, depending on the impact of past modelling reports and their dissemination into different layers of society.

An important issue is the one of spatial scale of models, and whether they consider the renewable energy to be produced on the spatial scale of the institution issuing the model and the users using the model. For example, an issue, which is rarely explicitly mentioned in such models is whether, for example, the EU has the right to explore and exploit (renewable) energy in other countries, assuming that these other countries would accept this in a democratic way, knowing that the EU stresses fiercely its values and even tries to export them around the world. In a recently published EU guideline, it is mentioned that : "[the EU] *is at the forefront of the fight against climate change and its consequences; as it plans to keep growing, it helps neighbouring countries prepare themselves for EU membership; and it is building a common foreign policy which will do much to extend European values around the world*" (European Parliament, n.d.).

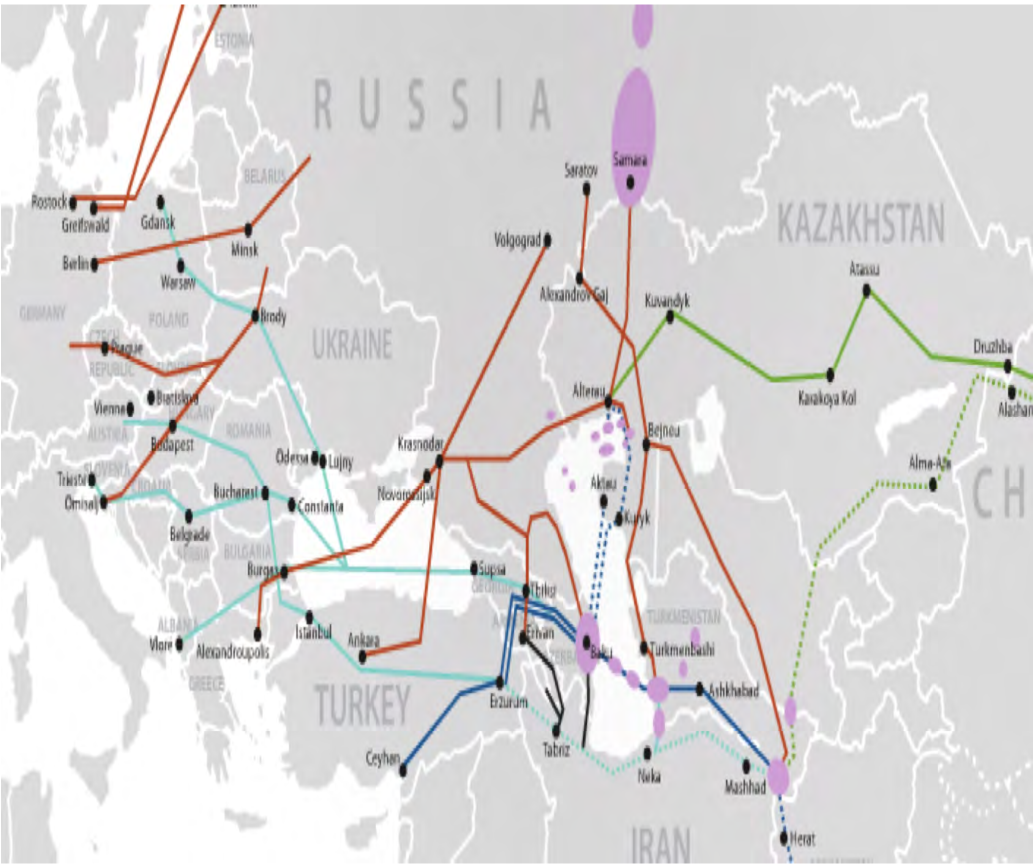
It can be interesting to know, to which extent institutions reflect on whether the values associated with large-scale renewable energy projects around the world are compatible with the values it defends on its territory. In the EU context, an example of a large-scale deployment of renewable energy is currently proposed by the DESERTEC-Atlas project, an initiative of the German Association of the Club of Rome ("DESERTEC Foundation - About," n.d.), or the Noor Ouarzazate Concentrated Solar Power Project of the World Bank (Mobarek, Sameh, 2016). When looking at the implementation plans of planned oil pipelines and planned solar energy transmission lines (figure 1, figure 2), it is clear that there is still room for reflection on the issue of scale.

On the other hand, efforts are ongoing to integrate the renewable wind energy network of the North sea (Gruenig, O'Donnell, 2016). Two examples of these are the North Seas Countries' Offshore Grid Initiative (NSCOGI) in which 10 north sea-countries collaborate to establish a common distribution grid and the Kriegers Flak project, a collaboration between Denmark, Sweden and Germany to establish a common 600 MW offshore wind grid. The NSCOGI project started with a Memorandum of Understanding in 2010 and is still in its development stage (ENTSO-E 2015) and the Kriegers Flak project is in the stage of asking funding from the European Investment Bank.

A balance should be sought on European level between energy use and supply, and the associated risk of conflicts, disturbing cultural values and reverting efforts being carried out to ensure prosperity around the world. The current Syrian war, a result of conflicts on scarce oil, might be replicated in the future in the Middle-East and Africa because of renewable energy conflicts if no answers are sought to the question of scale and territory (Figures 1 and 2). The future will determine whether the European societies will arrive to consciously assess the consequences of a consistent energy demand and balance it with potential security issues originating from foreign resource extraction, be it renewable or nonrenewable.

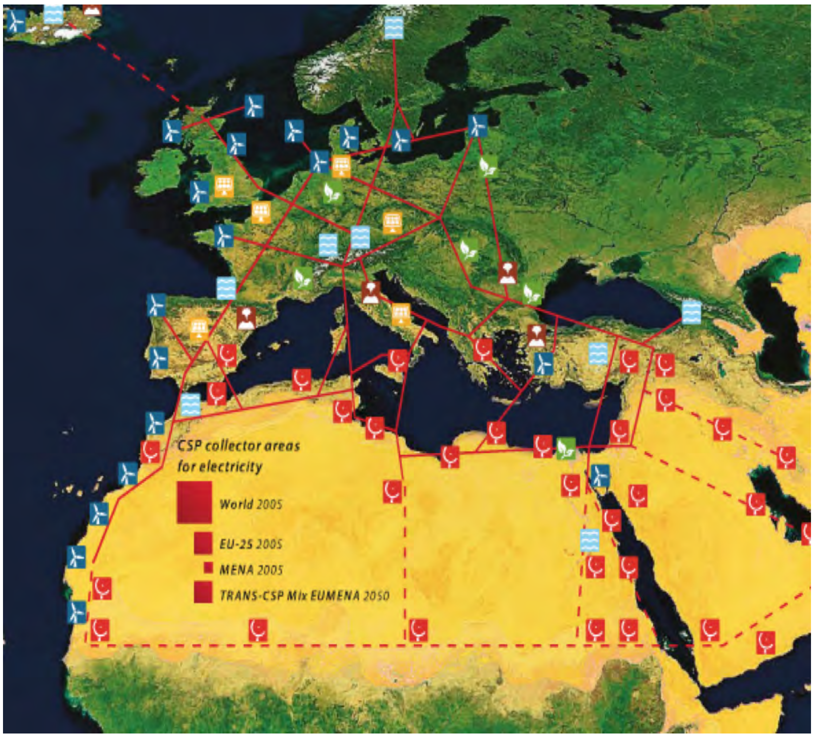
Social and geopolitical aspects discussed here, despite being very important, are not usually taken into account in macroeconomic energy-climate models. To ensure feasible modelling results, those aspects are to be discussed in the models' assumptions.

Figure 1: Planned oil pipelines in the Middle-East



Source: Desertec Foundation

Figure 2: renewable energy deployment around the equator (left)



Source: Desertec Foundation

Current macroeconomic energy-climate models

There are two main types of macroeconomic energy-climate models. The first type is represented by the models that link extensive energy and climate models but do not fully integrate them. The MESSAGE-MAGICC model used by the IPCC is an example of such models, where the energy module is connected to the climate model via its emissions part; the energy sector outcomes are used as an exogenous input for atmospheric GHG emissions change. Such models usually belong to the optimization class of models and seek for minimizing energy costs and atmospheric emissions. Another type of macroeconomic energy-climate models are integrated models, where the energy and climate sectors are connected and designed as interconnected parts of the same model's structure. Macroeconomic energy-climate models started being widely used after the year 2000. They aim at exploring energy scenarios where carbon emissions can reach the level corresponding to a 2°C atmospheric temperature increase, and where technological, resource availability and costs limitations are addressed.

Table 2 : Review of Macroeconomic Energy-Climate Models

Name of the model	*Methodology; Stand alone / Hybrid*	*Addressing resource limitations*	*Assumptions about RES*	*Addressing emissions*	*Timescale*
C-Roads (MIT)	System Dynamics Simulation model, stand alone	Only fossil fuel resources limitations are addressed	No resource limitations for RES, no connection to material requirements for RES. Renewable energy sources are seen as carbon neutral ones.	Emissions modelled as a stock. No feedback from climate change to energy resource availability.	1850-2100
MINICAM (Mini Climate Assessment Model) (Pacific Northwest National Laboratory)	Partial equilibrium model; Stand alone	Only fossil fuel and uranium resources and limitations are addressed	No resource limitations for RES. Renewable energy sources are seen as carbon neutral ones.	Emissions modelled as variables.	1990-2095
MARIA Model (Multiregional Approach for Resource and Industry Allocation)	Non-linear optimization model to assess the interrelationships among economy, energy, resources, land use and global climate change; Stand alone	Only fossil fuel resources limitations are addressed.	Renewable energy sources are seen as carbon neutral ones	Emissions modelled as variables.	1980-2060
Felix Model (Functional	System Dynamics	Only fossil fuel	Renewable energy	Climate sector and emissions	1900-2100

Enviro-economic Linkages Integrated neXus); IIASA	Model of social, economic, and environmental earth systems and their interdependencies; Stand alone	resources limitations are addressed.	sources are NOT seen as carbon neutral ones. There are CO2 emissions from RES.	in particular have the same structure as the C-ROADS Model.	
MESSAGE-MAGICC (Model for Energy Supply Energy Alternatives and Their General Environmental Impact - Model for the Assessment of Greenhouse Gas Induced Climate Change); IIASA	Hybrid model - Energy supply and energy service demand model connected to the probabilistic climate model	Only fossil fuel resources limitations are addressed.	Renewable energy sources are NOT seen as carbon neutral ones. There are carbon emissions from RES.	Climate is presented as a full-fledged model connected with the energy model via emissions part	1990-2400

None of the models analysed addresses the material resource limitations for renewable energy. Even though there are available studies addressing the problem of critical material need for renewable energy production (WWF report, 2014; Garcia-Olivares, 2011), their results are not reflected in the macroeconomic energy-climate models. Most of the models assume that renewable energy technologies are carbon neutral, and that there is no feedback from climate change effects to renewable energy resources availability. Addressing the limits of critical materials for renewable energy sources, as well as a feedback from climate change to renewable energy sources availability in energy-climate models, could help building more feasible renewable energy transition scenarios for the future and increase the accuracy of risk assessment associated with renewable energy use.

Modelling energy and climate scenarios in EU using GEM-E3 and PRIMES

A number of models used for analysing and simulating EU decarbonization pathways exist (Capros, 2014). Those models are used for informing better policy making and their modelling outputs serve as a guidance for EU policy documents. Considering the complexity policy making for the climate, it is important to be sure that such models produce feasible results and are based on realistic assumptions about economy, environment and energy systems.

GEM-E3 (Capros, 1997) and PRIMES (E3MLab, 2016) are two of the most widely used models for energy and climate change mitigation in the EU. Beyond this, together with the GAINS (Greenhouse Gas - Air Pollution Interactions and Synergies) model of the International Institute for Applied Systems Analysis (IIASA) it is possible to carry out an energy-economy-environment policy analysis in a closed-loop. The results of these models' simulations were used, in particular, for scenario analysis in the Energy Roadmap 2050 (2011) and for designing A Roadmap for Moving to a Competitive Low Carbon Economy in 2050 (2011).

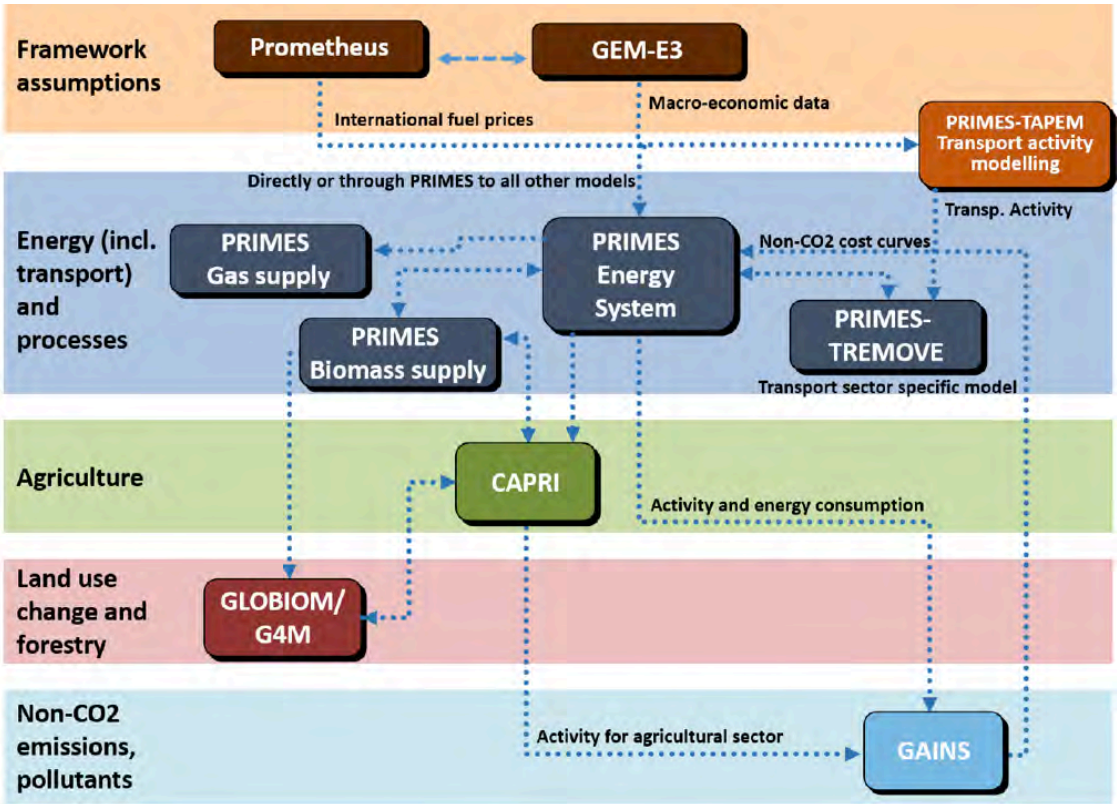
Originally GEM-E3 and PRIMES were designed as stand-alone models used for analysing the global economy and EU energy markets. For the purpose of addressing the needs for climate and energy policy making at the EU level these two models were coupled into the one hybrid structure. The intention of coupling the models aimed to support better climate and energy decisions via addressing limitations of both GEM-E3 and PRIMES (Capros,1996).

PRIMES is a partial equilibrium model which simulates equilibrium for energy supply and energy demand for all the EU member states until 2050. This model contains explicit and detailed information on energy technologies both on the supply and demand side. PRIMES is primarily directed to policy analysis in the field of security of energy supply, pricing policy, cost for climate mitigation, energy efficiency and standards on energy technologies (Capros, 2014).

GEM-E3 is a global scale multi-regional economic model which simultaneously represents 37 World regions including 24 European countries. It is a dynamic computable general equilibrium model that covers the interactions between the economy, the energy system and the environment. It provides quantitative results until 2050. Analysing global climate issues is one of the intended policy applications of GEM-E3. For this, GEM-E3 calculates and evaluates atmospheric emissions and their damage using cost-benefit analysis as the main approach for selecting the best energy and climate policy combinations.

GEM-E3 as a stand alone model cannot address technological aspects of different energy technologies which is important for assessing substitution possibilities and costs in production and consumption. At the same time PRIMES as a stand alone model lacks the interconnection between energy supply and demand and other economic sectors. Thus, GEM-E3 coupled with PRIMES performs energy-economy-environment policy analysis in a closed-loop computing energy prices in equilibrium and covering with engineering detail country-specific energy systems and the overall energy market in the EU.

Figure 3 : GEM-E3 and PRIME MODELS (2016)



Source: European Commission (2016, p. 16)

GEM-E3 and PRIMES are very oriented towards the price-driven equilibrium paradigm. They represent market clearing mechanisms and related behaviours of market agents as the main explanatory force in the models. Consequently, the assumptions of GEM-E3 and PRIMES mentioned in the models' documentation are mainly oriented at explaining market theories behind models' structures within existing technological limits.

Resulting scenarios from GEM-E3 and PRIMES simulations are focused on an energy technologies mix and a climate policy mix that would simultaneously minimize cost and atmospheric emissions. Thus, the main outputs from such scenarios are numerical parameters as energy efficiency, renewable energy sources penetration, percentage of nuclear power use, CCS deployment and transport electrification.

Since deployment of renewable energy is one of the central elements of climate and energy policy simulations, the models' assumptions of modelling renewables are of a high importance. Renewable energy technologies assumptions mentioned in PRIMES documentation allow to conclude that both nonrenewable and renewable energy technologies are modelled in a conventional way. This means that limits of resource availability are present only for fossil fuels, and none of renewable energies is associated with resource scarcities for harvesting. Feedback between climate change and renewable energy availability is also not present in the model structure. However, there are some limitations for renewable energy of a technological origin and availability present in PRIMES. They include the difficulties of getting access to resources, the availability of sites, acceptance, grid connection difficulties, and for biomass land and waste energy resource availability are considered.

Considering the arguments made in the first part of this paper, the absence of assumptions on resource limitations for harvesting some types of renewable energy and the absence of feedback between climate change and renewable energy availability can potentially lead to inaccurate modelling results, especially when it comes to long-term planning. Political aspects of energy resource availability associated with resource conflicts and additional cost could potentially have policy implications and demonstrate the need for trade-offs at both global and national levels.

Interestingly, there are studies and policy reports at the EU level, which analyse possible implications of material scarcity for harvesting renewables and potential economic and political risks associated with them. One of the elaborated reports of this kind is Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector (Moss, 2013). Integrating the findings of such reports with the assumptions of macroeconomic energy-climate models in the EU could bring new important policy insights and help better decision-making for mitigating climate change.

Conclusion

Making feasible projections on the possible impact of the employment of particular renewables to minimize effects on climate change is only possible if all factors influencing the development of renewables are treated in a heuristic way. Moreover, they should all be treated based on empirical gathered knowledge.

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4. Paper III: Integrated Assessment Models (IAM): How to integrate Energy, Climate and Economics?

Integrated Assessment Models (IAM)

How to integrate Energy, Climate and Economics?

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Abstract

Economics, energy and climate are the three main building blocks of the integrated assessment models (IAM), and they belong to the same system, a global integrated system in which loops and time delays show the main dynamics - a methodology well known as system dynamics (SD). In IAMs, the laws of nature and human behavior are reduced to their essentials to understand how increased Greenhouse Gases (GHGs) affect temperature, and how temperature (increase?) leads to economic damage. IAMs are usually associated with three purposes: assess climate change control policies; constructively force multiple dimensions of the climate change problem into the same framework; quantify the relative importance of climate change in the context of other environmental and non-environmental problems facing mankind. This article reviews several IAMs - World3, DICE, IMAGE, MESSAGE, GEM-E3, and REMIND, to understand their structure, goals, policy evaluation or policy optimization and dynamics. We aim to identify the future challenges for the IAM community.

Keywords

Climate, Economics, Energy, Feedback Loops, IAM, System Dynamics

From the pioneering work of Forrester (1965, 1969) and Meadows (1972) with the World 2 and World 3 models based on system dynamics methodology, to the models developed by IPCC experts (2001, 2015), modeling from a global environmental prospective (Matarasso, 2003) has become increasingly integrated. In the 1990's, some models were developed to combine different key elements of biophysical, social, and economic systems into one integrated system (Dowlatabadi, Morgan, 1993, 1995). What we call today Integrated Assessment Models (IAMs) became powerful tools for thinking, simulation and decision support.

Kelly and Kolstad (1999, p. 3) defined an integrated assessment model as "*any model which combines scientific and socio-economic aspects of climate change primarily for the purpose of assessing policy options for climate change control*". Integrated assessment induces an "*interdisciplinary and participatory process of combining, interpreting and communicating knowledge from various scientific disciplines to enable understanding of complex phenomena*" (Parker, 2002).

Weyant et al (1996) gave three purposes for integrated assessment: (1) Assess climate[1] change control policies, (2) Constructively force multiple dimensions of the climate change problem into the same framework, (3) Quantify the relative importance of climate change in the context of other environmental and non-environmental problems facing mankind. The final goal of integrated assessment is to build the best possible response[2], with present knowledge, to the questions asked by decision makers about environmental issues (Kieken, 2003). This goal is usually achieved by integrating work from various disciplines into an interactive process that includes researchers, managers, and stakeholders. The release and sharing of knowledge between communities is ensured by the implementation of three kinds of complementary tools[3]: (1) Integrated assessment computer models designed as methodological frameworks for interdisciplinary work which are the means to integrate knowledge from a variety of disciplines, (2) Qualitative scenarios to take into account what is not modellable, (3) Participatory methods involving stakeholders other than scientists and politicians, with the aim of improving the acceptability of decisions through a better understanding of the issues, legitimizing the decision-making process through the early involvement of stakeholders, and introducing non-expert knowledge of the issues).

IAMs are usually divided into two categories: policy optimization IAMs and policy evaluation IAMs. Policy optimization IAMs search for the optimal policy. They can be split into three principal types: (i) Cost/benefit models which try to balance the costs and the benefits of climate policies, (ii) Target based models which simulate the effect of an efficient level of carbon abatement in the world economy, (3) Uncertainty based models which deal with decision making under conditions of uncertainty (Manne, Richels, 1992; Nordhaus, 1994). Many policy optimization models start with a market economy in which the regulatory instrument is a tax and then convert the model to an equivalent problem which finds the optimal emissions. Such models maximize the weighted sum of utilities where the weights are adjusted until individual budgets balance (which is equivalent to a Pareto Optimum (second welfare theorem)), or start with optimal emissions and convert the results into a tax. So optimization models are standardized and provide a description of the world, given the assumptions of the equivalence theorems. Policy evaluation IAMs are well-known as simulation models.

[1] If energy system and macroeconomic structure have been usually connected, the integration of climate in a global system is a recent practice. Climate has been invited to the debate following the various IPCC reports (1990, 2018) and the controversies related to global warming.

[2] Pearson and Fisher-Vanden (1997, p. 593) considered that IAMs brought four broad contributions: evaluating potential responses to climate change; structuring knowledge and characterizing uncertainty; contributing to broad comparative risk assessment; and contributing to scientific research.

[3] Rotmans and Dowlatabadi (1998) noted that current integrated assessment research used one or more of the following methods : (i) computer-aided IAMs to analyze the behavior of complex systems, (ii) simulating gaming in which complex systems are represented by simpler ones with relevant behavioral similarity; (iii) scenarios as tools to explore a variety of possible images of the future; (iv) qualitative integrated assessments based on a limited heterogeneous data set, without using any models.

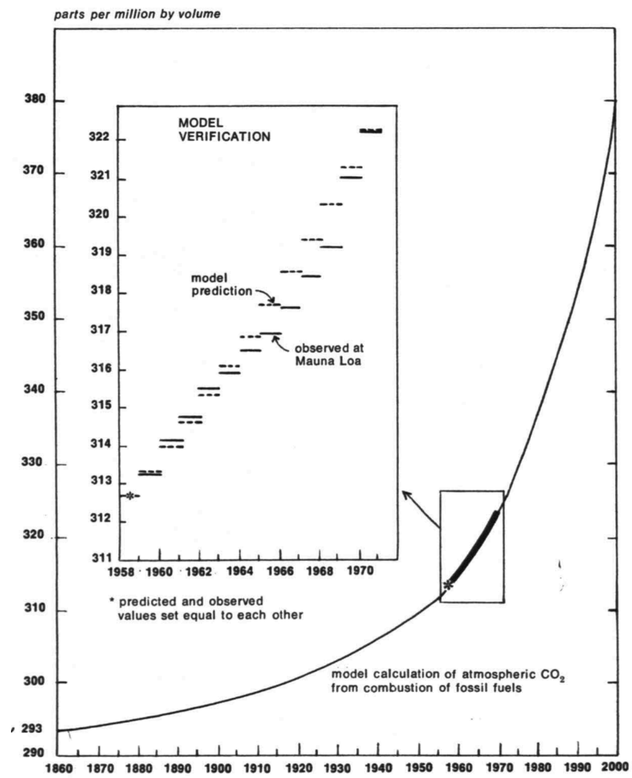
They include deterministic projection models in which each input and output takes a single value, and stochastic projection models in which at least some inputs and outputs take a range of values. Policy evaluation models take actions by agents and governments as given, provided by policy proposals, assumption, observation and expert opinion.

In this article, we propose to review 6 IAMs (World 3, DICE, IMAGE, MESSAGE, GEM-E3 and REMIND) to understand how these models are able to integrate Energy, Climate and Economics. We will resume their main results in a table to present goals, structure, policy evaluation, policy optimization, and dynamics associated with the models. We will identify the future challenges for research design and policy decisions.

1. World 3 - the first design of an IAM?

In the 1972 *Limits to Growth* report, the climate system is not part of the model. The pollution variable is captured by the concentration of carbon dioxide in the atmosphere. Meadows et al (1972, p. 71) introduced a positive loop: the more industrial production increases, the more fossil energy (coal, oil and natural gas) is used; this releases CO2 into the atmosphere and causes an increase in mortality.

Figure 1: Concentration of CO2 in the Atmosphere

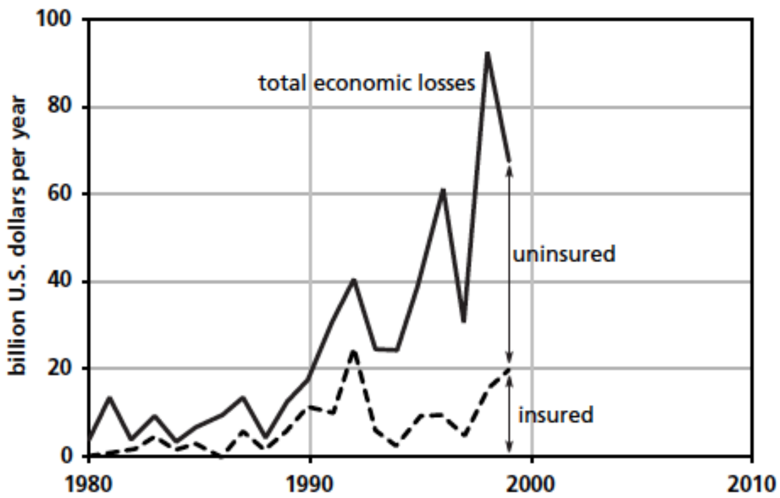


Source : Meadows et al. (1972, p. 72)

It would be necessary to wait for the publication of *Beyond The Limits* (1992) for climate to be explicitly integrated into system dynamics, but it was only mentioned in Chapter 3 (The Limits: Sources and Sinks) on pollution and waste. While global climate change is clearly presented as the new challenge for the coming years (scientific evidence of global warming is accumulating), its analysis continues to feed into the growth debates: "*Many scientists believe that the next global limit humanity will have to deal with is the one called the greenhouse effect, or the heat trap, or global climate change*" (1992, p. 92). Thus, global climate change cannot be detected in the short term, but over decades. To these long-term observations, three types of uncertainties must be added: 1. What would the global temperatures be without human intervention? A reduction in growth may not be sufficient to reduce CO2 concentrations if they increase naturally in the long term, 2. What are the consequences of global warming on precipitation, winds, ecosystems and human activities at particular locations on Earth? 3. How to understand all the loops associated with carbon and energy flows. The modelling of such a system is complex and control loops can be used to stabilize CO2 emissions (the oceans can absorb some of them).

The publication of *Limits to growth, the 30 years update* (2004), deserves attention, as the climate generates many loops in World 3. The report does not hesitate to target economists, the main climate skeptics and to highlight the consequences of climate change on economic activities, and therefore on economic growth: "*More scientists, and now many economists as well, believe the next global limit humanity will have to deal with the greenhouse effect, or global climate change... Even some economists - a group well known for its skepticism about environmentalist alarmism - are becoming convinced that something unusual and significant is going on in the atmosphere, and that it may have human causes*" (2004, p. 113-115).

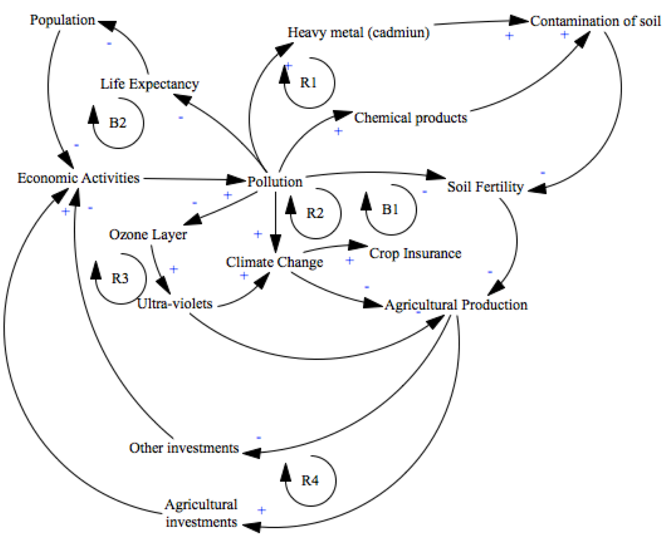
Figure 2: Worldwide Economic Losses from Weather Related Disasters



Source : Meadows et ali. (2004, p. 117)

Climate change is causing economic losses that call into question the viability of insurance systems (the 1990s and 2000s marked a break in the trend, with the share of damage not giving rise to big reimbursement increases). Scenario 2 (Global Pollution Crisis) introduces the damaging effects of pollution and climate change. The positive loop is as follows: an increase in pollution reduces land fertility, which in turn reduces agricultural production, investments move to agricultural sector to maintain food production and decrease in other sectors, pollution leads to lower life expectancy and increased mortality. This loop is reinforced by three effects: land contamination by heavy metals and chemicals, climate change that randomly and repeatedly alters agricultural production, and ultraviolet radiation related to ozone depletion.

Figure 3: Positive and negative loops in the scenario "more pollution"



This work has been widely criticized by economists, William Nordhaus (1972, 1973) was the main architect of this critique. In an article co-written with James Tobin entitled "Is Growth Obsolete? ", Nordhaus responded to the report: (« *We mention this point now because we shall return later to the ironical fact that the antigrowth men of the 1970s believe that it is they who represent the claims of a fragile future against a voracious present*", 1972, p. 4) by mobilizing theory around three questions: 1. The measurement of economic growth, 2. The link between growth and natural resources, 3. The link between population growth rates and economic well-being.

A year later, Nordhaus (1973) repeated his critique, targeting Forrester's *World Dynamics*. The title "World Dynamics Measurement without data" and the content of the article are unequivocal. « *What is the overall impression after a careful reading of World Dynamics? First, the dynamic theory put forward in the work represents no advance over earlier work… Second, the economic theory put forth in World Dynamics is a major retrogression from current research in economic growth theory… Third, Forrester has made no effort in World Dynamics to identify any relation between his model and the real world…*

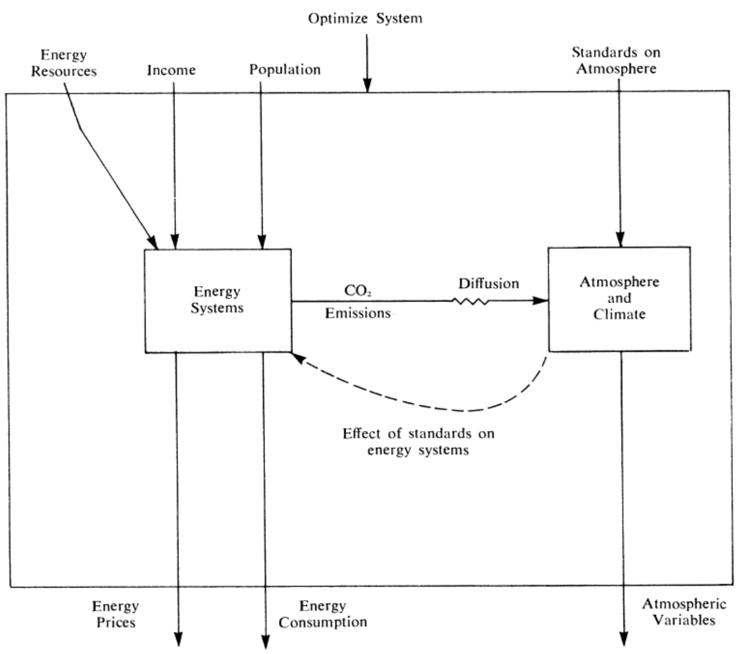
Fourth, the methodology of modelling in World Dynamics differs significantly from other studies of economic systems…Fifth, the predictions of the world's future are highly sensitive to the specification of the model… Sixth, there is a lack of humility toward predicting the future" (1973, p. 1183).

2. DICE - the Carbon Dioxide Problem

It is in this context that Nordhaus would undertake his research "Resources as a constraint to growth" (1974), into the management of energy resources, and then take into account the impact of CO2 concentration in the atmosphere. He concludes that assuming that "*10 percent of the atmospheric CO2 is absorbed annually (G. Skirrow), the concentration would be expected to rise from 340 ppm in 1970 to 487 ppm in 2030 - a 43 percent increase*" (1974, p. 26). His paper is a first attempt at integrated climate modelling. It is rudimentary (only the CO2 variable is taken into account), but it does reflect the debates of the 1970s. Against the backdrop of the energy crisis, Nordhaus intended to develop a global energy model that could be coupled with a climate model. Nordhaus presented this theoretical framework in two articles, one presented to the Cowles Commission (Strategies for the Control of Carbon Dioxide, 1976), the other published in The American Economic Review (Economic Growth and Climate: The Carbon Dioxide Problem, 1977).

Figure 4 provides an overview of the model used by Nordhaus to study carbon dioxide emission control strategies.

Figure 4: Optimization model of energy and environmental system



Source: Nordhaus (1977, p. 343)

The "energy system" block is a system combining market mechanisms and economic policies. The key variables are energy, natural resources, income, and population. The interaction of supply and demand leads to a trajectory of optimization of prices and consumption over time. To take into account externalities, such as the carbon cycle, Nordhaus proposes to take into account CO2 emissions and distribution. This step leads to the imposition of standards on atmospheric concentrations (right side of the figure). By imposing such standards, it becomes possible to close the loop and force the energy system to act on the structure of supply and demand. Nordhaus is examining two strategies to keep atmospheric CO2 concentrations at a reasonable level. The first strategy is to reduce carbon dioxide emissions. This means replacing high CO2 fuels with low CO2 fuels. The second strategy is to offset the effects of carbon dioxide emissions or use new industrial processes (environmental technologies) to "suck" carbon dioxide from the atmosphere. In order to avoid "*the odor of science fiction*" (1977, p. 343), Nordhaus favors the first strategy by seeking to optimize the system based on standards.

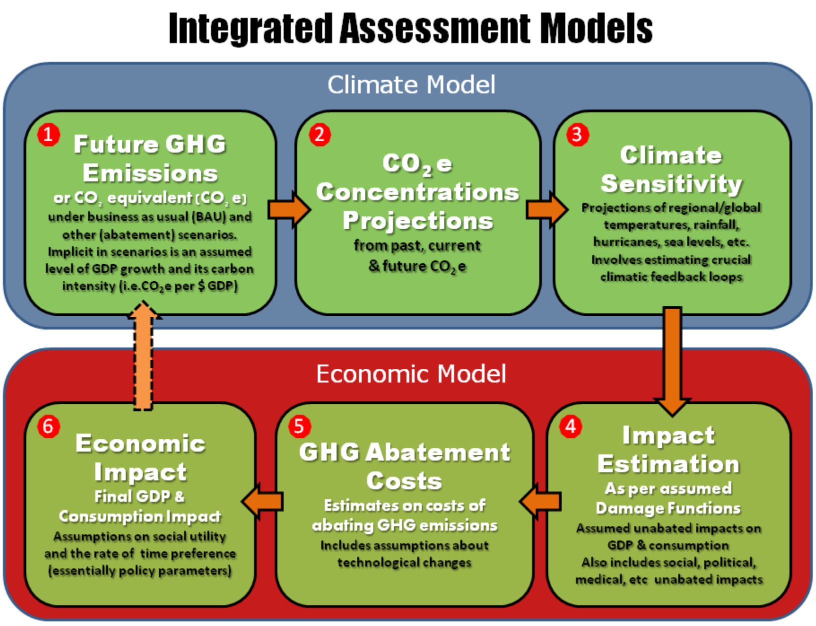
It was not until the 1990s that the DICE (Dynamic Integrated Model of Climate and the Economy) and RICE (Regional Integrated Model of Climate and the Economy) family of models was born (Nordhaus, 1992, 1994). The DICE model is a dynamic optimization model (Ramsey, 1920) which seeks to estimate the optimal GHG reduction trajectory. The optimal trajectory can be interpreted as the most effective way to slow climate change, taking into account inputs and technologies (Veille-Blanchard, 2007). It can also be interpreted as a competitive market balance in which externalities are adjusted using appropriate social prices for GHGs. In the DICE model, emissions include all GHGs, however, those associated with CO2 are preferred. GHG emissions, which accumulate in the atmosphere, can be controlled by increasing the prices of inputs (such as energy) or GHG-intensive products. Climate change is captured by the overall average global temperature, a variable used in most current climate models. The economic impacts of climate change are assumed to increase as the temperature increases.

In the space of two decades, the DICE model has been a huge success, for which three reasons can be given. The first reason is the multiple revisions proposed by Nordhaus: an intermediate version (Nordhaus, 2008) and an updated version (Nordhaus 2017). The DICE model has been iterated many times, incorporating recent economic and scientific results and updated economic and environmental data. The second reason is based on a detailed description of the model (Nordhaus, Sztorc, 2013) with the availability of the DICE manual and the possibility of carrying out simulations. The third reason is the media coverage of DICE through the publications and work of the IPCC (since 1995) and many energy agencies (including the US agency).

To this, we add a fourth reason that affects the way Integrated Assessment Models (IAM) are approached today. This fourth reason is that the DICE model has initiated a way of thinking about integration, which can be summarized by the following process: integration of CO2 emissions, impacts on economic activities, economic policy measures. As a result, Climate, Energy, and Economics are now the main building blocks for integrated assignment models (Ha-Dong, Matarasso, 2006; Gladkykh, Spittler, Dierickx, 2017).

Integrated models are not limited to the DICE model, other models emerged in the 1990s - ICAM (Dowlatabadi, Morgan, 1993), IMAGE (Alcamo, 1994), MERGE (Manne et al, 1995), MiniCAM (Edmonds et al, 1996). Some like IMAGE (Integrated Model to Assess the Global Environmental) even follow in the footsteps of World 2 and World 3, adopting an architecture built around the main drivers (population, economy, politics, technology, lifestyle and resources) of the human and earth ecosystems. Thus, alongside small, simplified and discipline-based models (DICE and economics), there are global, complex and interdisciplinary models (World 3, IMAGE). These two main families of models have contributed to enriching the debate about the integrated approach to climate change, each with its strengths and weaknesses.

Figure 5: Coupling climate system and economic system



Source: deconstructingrisk.com

The 2000s were marked, not by rivalry between models (although it does exist), but by a reflection about the processes of integration (Matarasso, 2003) and evaluation (Schwanitz, 2013) of IAMs (Pearson and Fisher-Vanden, 1997). This is particularly visible through the many definitions which have been used. Integrated assessment can thus be defined as "*an interdisciplinary and participatory process aimed at combining, interpreting and communicating knowledge from various scientific disciplines to enable the understanding of complex phenomena*" (Parker, 2002). It aims to build the best possible response, in the current state of knowledge, to questions asked by decision-makers on environmental issues (Kieken, 2003). This objective is generally achieved by integrating the ongoing work of various disciplines into an interactive process that includes researchers, managers, and stakeholders. The circulation and sharing of knowledge between communities is ensured by the implementation of three families of complementary tools: (1) Computer models of integrated assessment designed as a methodological frameworks for interdisciplinary work and the means of integrating knowledge from various disciplines, (2) Essentially qualitative scenarios to take into account what is not modellable, (3) Participatory methods involving stakeholders other than scientific and political (the aim here is to improve the acceptability of decisions through a better understanding of the issues; to legitimize the decision-making process through the early involvement of the actors concerned; to introduce non-expert knowledge).

These interdisciplinary computerized models, designed to address issues of climate impact, climate adaptation and climate change, are still not robust. While each discipline provides some knowledge about the processes which determine the evolution of the Earth/Society system, their interaction poses a number of problems. For example, climatologists' General Circulation Models (GCMs) do not allow us to study in detail the strategies for reducing greenhouse gas emissions. It is therefore necessary to look at the energy system in order to identify energy production and transformation technologies. These technologies must, in turn, be included in a macroeconomic model, designed to understand the major monetary and financial balances that regulate the economy. To address these limitations, the modelers have developed a modular approach, based on the coupling of existing models, which are themselves based on a discipline. Integration is based on the following: (1) Climate models (more or less complex), (2) Energy system models, (3) Macroeconomic models of global activity, (4) Carbon cycle models (often related to land use). These couplings generate a multitude of challenges (depending on whether the modules are solved simultaneously or successively or according to the finesse of the different representations of the modules), which demand the creation of a real network of modelers, users, and decision-makers at the IAM level. This is the price to pay for the necessary changes in our behavior with regard to climate change.

3. MESSAGE - Shared Socioeconomic Pathways

The IIASA IAM framework is a combination of five different models – The energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregate macro-economic model MACRO, and the climate model MAGICC. These five models provide inputs, drivers and dynamics to describe alternatives futures for societal development. Scenarios of global development focus on the uncertainty of the future conditions of society, describing future societies that can be combined with climate change projections and climate policy assumptions to produce integrated scenarios to explore climate mitigation, climate adaptation and residual climate impacts in a consistent framework. Society's development scenarios consist of qualitative and quantitative components (Raskin et al, 2005). Quantitative components introduce assumptions for variables such as population, economic growth (GDP), technological progress, food, etc which are quantified and used as inputs to model energy use, land use, GHG emissions (Rothmans et al, 2007). Qualitative storylines describe the evolution of society such as quality of institutions, environmental awareness, and political stability to "*provide a certain logic to the multiple assumptions and to help to define possible developments for those areas where formal modeling is not meaningfully possible due to ignorance and complexity*" (Van Vuuren et al, 2012, p. 888). If the process to develop a new set of integrated scenarios describing climate, society and environmental change, is still happening, a few researchers (Krieger et al, 2012, O'Neill et al, 2014, Kriegler et al, 2014, Riahi et al, 2017; O'Neill et al, 2017; Van Vuuren et al, 2017, Bauer et al, 2017) have introduced alternative pathways of future development of society called *shared socioeconomic pathways* (SSPs)[4]. A conceptual framework has been produced for the development of SSPs (O'Neill et al, 2014, 2015) and for the combination of Integrated Assessment Model (IAM) scenarios based on SSPs with future climate change outcomes and climate policy assumptions, to produce integrated scenarios and support other kinds of integrated climate change analysis. SSPs describe plausible alternative changes in aspects of society such as demographic, economic, technological, social, governance' and environmental factors.

Figure 6: Five shared Socioeconomics Pathways

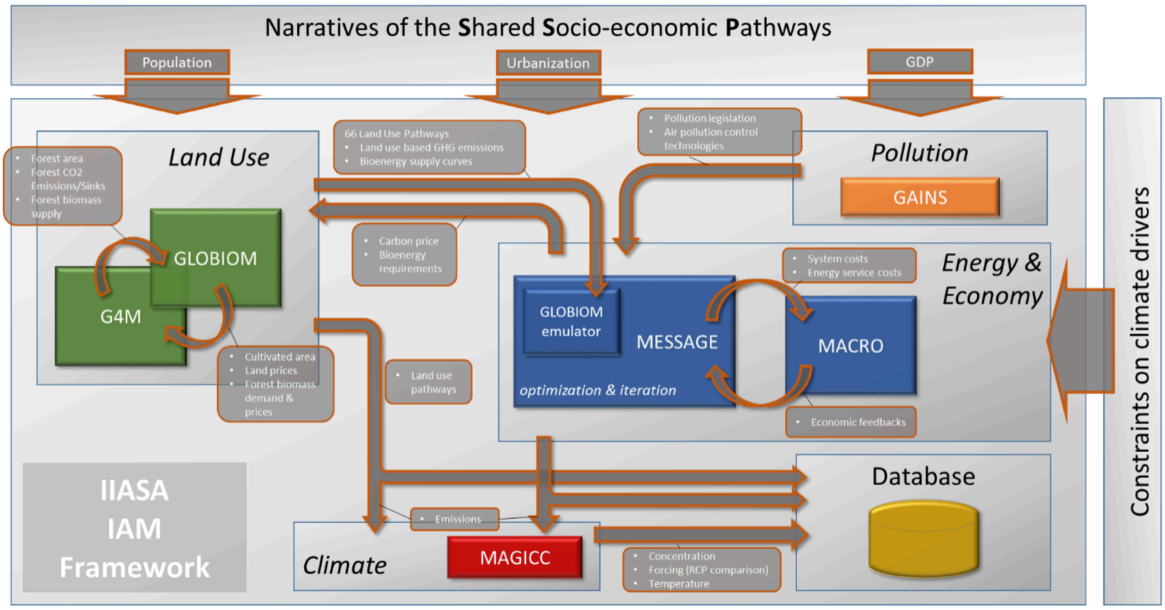
Source: O'Neill et al (2014, p. 391; 2015, p. 2)

[4] "*We define SSPs as reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies* » (O'Neill, 2014, p. 387 – 388).

Five shared socioeconomic pathways have been proposed to represent different combinations of challenges to climate change mitigation and to climate adaptation (O'Neill et al, 2014, 2015): SSP1 (Sustainability: taking the green road), SSP2 (Middle of road), SSP3 (High challenge: Regional Rivalry, a rocky road), SSP4 (Adaptation challenges Dominate: Inequality, a road divided), SSP5 (Mitigation challenges dominate: fossil fueled development, taking the highway).

From these five SSPs, three following narratives have been introduced into the IIASA – IAM framework: SSP1 (sustainability), SSP2 (middle of the road) and SSP3 (regional rivalry, a rocky road).

Figure 7: Narratives of the Shared Socio-economic Pathways in IAM



Source: http://data.ene.iiasa.ac.at/message-globiom/overview/index.html

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) represents the core of the IIASA (International Institute of Applied Systems Analysis) IAM framework. It was developed in the 1980s. While it is possible to use the model on a global scale it has also been applied to various national energy systems. The model is a technology-rich bottom-up energy system model, which is very detailed on the supply side but not on the demand side. It is used for modelling the supply side and its general environmental impacts, planning medium- to long-term energy systems, and analyzing climate change policies on a national level or for global regions. This is possible because the model has been developed further and many hybrid versions exist. Some important aspects of energy system modelling have been integrated into MESSAGE (i.e. Stochastic MESSAGE, Myopic MESSAGE, MESSAGE-Access), while other relevant models are linked to it to some extent (i.e. from soft to hard link). The various hybrids of MESSAGE make it possible to apply

MESSAGE for a broad range of future scenario and policy analysis. The following hybrids exist:

(i) MESSAGE-MACRO: MACRO is a general equilibrium model (it was derived from GLOBAL 2100 and MERGE models) which maximizes the over time utility function of a single representative producer/consumer in each world region and evaluates energy demand. The main variables of the model are capital stock, available labor, and energy inputs, which together determine the total output of an economy according to a CES (Constant Elasticity of Substitution) production function. MACRO's production function includes seven energy service demands which are provided by MESSAGE (residential/commercial thermal, residential/commercial specific, industrial thermal, industrial specific, industrial feed stock, transportation, non-commercial biomass). The primary drivers of future energy demand in MESSAGE are forecasts of total population size and GDP at purchasing power parity exchange rates, denoted as GDP (PPP).

(ii) MESSAGE-MAGICC: MAGICC (Model for the Assessment of Greenhouse gas Induced Climate Change) covers several aspects related to climate change processes. These CLDs do not offer an exhaustive representation of GE3M dynamics. More precisely, MAGICC is a reduced-complexity coupled global climate and carbon cycle model which calculates projections for atmospheric concentrations of GHGs and other atmospheric climate drivers, like air pollutants, together with consistent forecasts of radiative forcing, global annual mean surface air temperature, and ocean heat uptake. Through the link to MESSAGE it is possible to investigate the impact of different energy pathways on the economic and energy system.

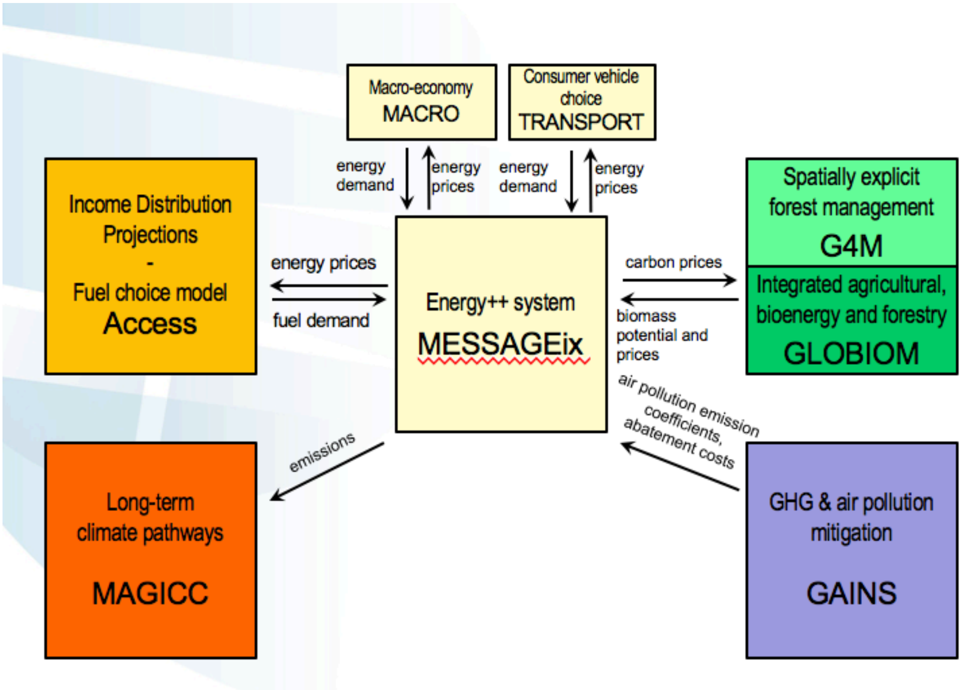
(iii) Linkages to models such as the agricultural model GLOBIOM (Global BIOsphere Management) and the air pollution one GAINS (Greenhouse gas – Air pollution Interactions and Synergies) permit the assessment of other possible effects of energy system developments in other relevant fields. GLOBIOM is a partial equilibrium model which shows the competition between different land use based activities including the agriculture, forestry, and bioenergy sectors. Production adjusts to meet demand for 30 economic regions. GAINS[5] was launched in 2006 as an extension of the RAINS model, which is used to assess cost-effective response strategies for combating air pollution (fine particles and ground level ozone). GAINS gives the historic emissions of 10 air pollutants and 6 GHGs for each country based on data from international energy and industrial statistics. The model may be used in two ways: (i) scenario analysis mode - it follows emission pathways from source to impact; (ii) optimization mode - it identifies where emissions can be reduced most cost effectively.

[5] GAINS is used for policy analyses under the Convention on Long-range Transboundary Air Pollution (CLRTAP) e.g. for the revision of the Gothenburg Protocol, and by the European Commission for the EU Thematic Strategy on Air Pollution and the air policy review.

Today, GAINS tools offer three ways to explain policy interventions which have multiple benefits: (1) Cost simulation, (2) Cost-effectiveness analysis to identify lowest-cost packages of measures, (3) Cost-benefit assessments that maximize net benefits of policy interventions.

Despite MESSAGE being originally developed as a bottom-up, technology-rich, supply-side focused model it is used for a wide range of integrated assessments. These assessments are possible because of the continuous development of the model as well as its linkages to other models, covering important aspects related to sustainable (energy) system development.

Figure 8: IIASA Integrated Assessment Framework



Source: Giddens (2018)

4. GEM-E3 - a General Equilibrium Model

GEM-3E (General equilibrium Model for Energy Economy Environment), partly funded by the European Commission (DG Research, 5th Framework programme) and by national authorities, is the result of a collaborative effort by a consortium involving National Technical University of Athens (NTUA – E3M lab), Katholieke Universsiteit of Leuven (KUL), University of Manheim, the Centre for European Economic Research (ZEW), and the Ecole Centrale de Paris (ERASME).

The model is used "*to examine the potential for the EU to gain a first mover advantage if adopts earlier than others ambitious GHG emissions reduction policies*" (Paroussos, 2018, p. 2). GEM-E3 provides details on the macro-economy and its interaction with the environment and the energy system. The model is able to fix the optimum balance of energy demand and supply, atmospheric emissions, and pollution abatement, simultaneously with the optimizing behaviour of agents and the fulfillment of the overall equilibrium conditions.

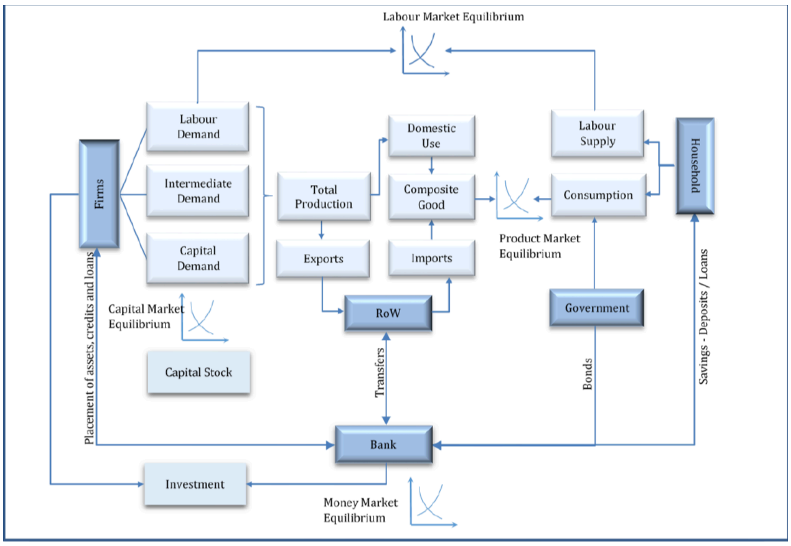
The model calculates the equilibrium prices of goods, services, labor, and capital which simultaneously clear all markets under the Walras Law (Capros, Van Regemorter, Paroussos, Karkatsoulis, 2015). The model follows a computable general equilibrium approach[6].

The main features of the model are as follows (Paroussos, 2018):

- it is a global and multi-regional model, treating separately each EU-15 member state and linking them through endogenous trade of goods and services.

- it includes multiple industrial sectors and economic agents, which permits the consistent evaluation of the distributional effects of policies. An economic circuit describes the relations between agents (firms, households, banks, etc) and the main drivers (capital, investment, exportations, importations, consumption, etc).

Figure 9: Economic circuit of GEM-3E



Source: Paroussos (2018, p. 7)

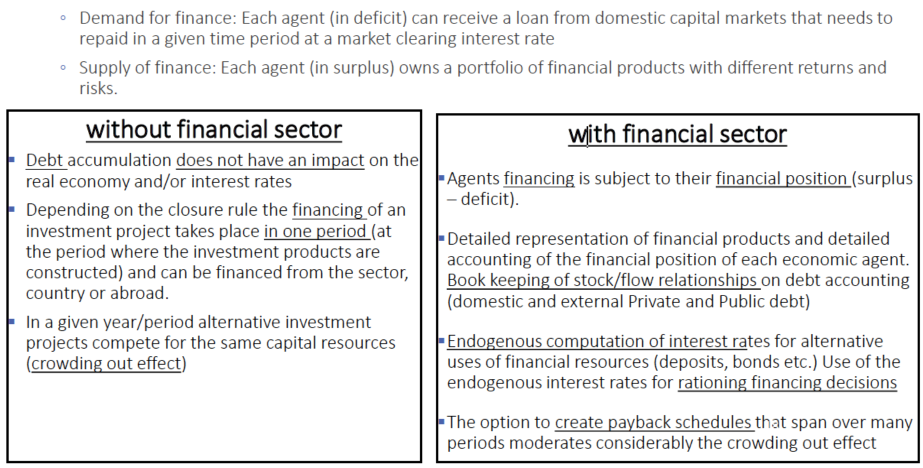
[6] The distinguishing features of general equilibrium modelling derive from the Arrow-Debreu economic equilibrium theorem and the constructive proof of existence of the equilibrium based on the Brower-Kakutani theorem. The Arrow-Debreu theorem considers the economy as a set of agents, divided into suppliers and demanders, interacting in several markets for an equal number of commodities. Each agent is a price-taker, in the sense that the market interactions, and not the agent, are setting the prices. Each agent individually defines his supply or demand behavior by optimizing his own utility, profit, or cost objectives. The theorem states that, under general conditions, there exists a set of prices that bring supply and demand quantities into equilibrium and fully (and individually) satisfy all agents. The Brower-Kakutani existence theorem is constructive in the sense of implementing a sort of trial and error process around a fixed point where the equilibrium vector of prices stands. Models that follow such a process are called computable general equilibrium models.

- it covers the major aspects of public finance including all substantial taxes, social policy subsidies, public expenditures, and deficit financing, as well as policy instruments (for environment and energy system). A financial/monetary sub-model is connected to the macroeconomic structure, following the IS/LM methodology.

- it is a dynamic, recursive over time, model, which involves the dynamics of capital accumulation and technology progress (measured by R&D expenditure by private and public sectors), stock and flow relationships, historically-based forecasts and spill-over effects.

- it proposes an explicit description of a detailed financial sector for each country that includes agent specific debt profiles and market clearing interest rates.

Figure 10: Computer General Equilibrium with financial sector



Source: Paroussos (2018, p. 18)

- it includes also a detailed representation of the power generation system (10 power generation technologies) and discrete representation of the sectors manufacturing clean energy technologies (wind, PV, electric cars, biofuels, etc).

Figure 11 : GEM-E3 model dimensions

Countries/regions	Each of the 28 EU MS, plus 18 other countries/global regions (All G-20 countries individually represented)
Sectors	51 production sectors including detailed representation of transport, power generation and clean energy technologies
Energy users	47 firms by country and households
Fuels	Biomass, Ethanol, Bio-diesel, Coal, Crude Oil, Oil, Gas
Emissions	All GHGs, both energy and process related
Energy technologies	Coal fired, Oil fired, Gas fired, Nuclear, Biomass, Hydro-electric, Wind, PV, CCS Coal, CCS Gas
Economic agents	Households, Firms, Government, Banks, Foreign Sector
Periodicity and time horizon	Annual to 2020, five-year time step to 2070, more suited for medium and long-term analysis
Policy applications	Capable of analyzing a wide range of policy measures (like ETS allowances, carbon taxes, investments in alternative power generation technologies and energy efficiency)
External sensitivities	Global energy prices, policy measures in non-EU countries, different uptake of low-carbon technologies
Model results/impact assessment	GDP, jobs, energy prices, consumer prices, sectoral production, budget deficit, competitiveness, balance of payments, energy use, GHG emissions, welfare

Source: Parroussos (2018, p. 4)

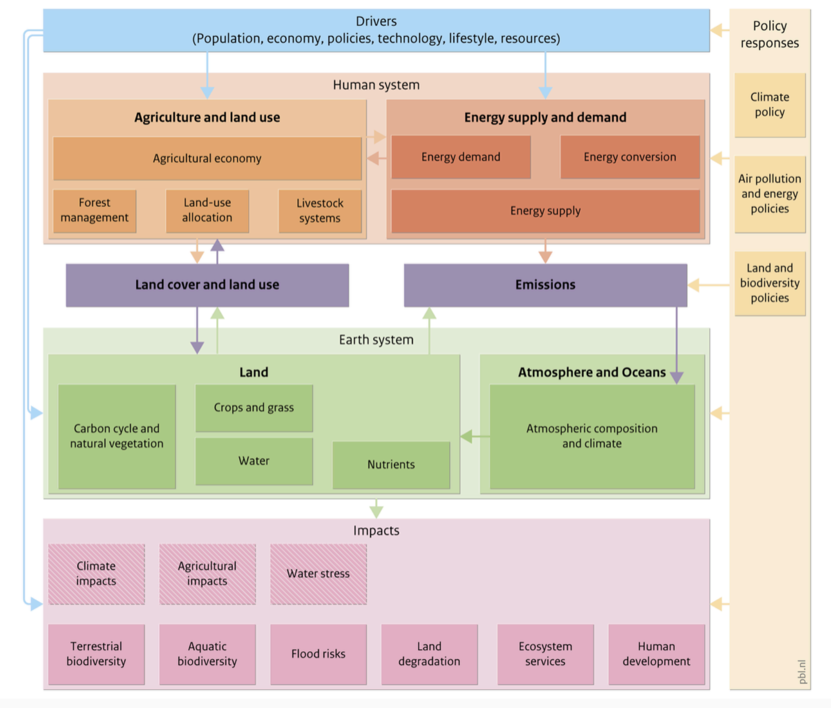
- it includes projections of the Input/Output Table (IOT) for country national accounts, employment, capital, monetary and financial flows, etc based on Eurostat data.

In general terms, the GEM-E3 model covers the general subject of sustainable economic growth and supports the study of related policy issues. Even if the model is based on economic theory (general equilibrium, price adjustment, carbon tax, emissions permits), it aims to analyze the global climate change issues for Europe, and provides an analysis of distributional effects (distribution among European countries and distribution among social and economic groups within each country).

5. IMAGE - a detailed biophysical system

IMAGE (Integrated Model to Access the Global Environment) is an ecological/environmental based model that simulates the environmental consequences of human activities. The first version of IMAGE was developed in the 1980s. Its main goal is exploring interactions between human and Earth systems to better understand how to approach multiple sustainability issues (i.e. climate change, biodiversity loss, human well-being). The objective of the IMAGE model is to explore the long-term dynamics and impacts of the global changes which result from interacting socio-economic and environmental factors (Stehfest et al, 2014). The latest improvements to IMAGE 3.0. focus on human development and explore the dynamics and trade-offs between different model sectors to reach sustainability goals.

Figure 12: IMAGE model schematic framework



Source: Stehfest et al., (2014)

IMAGE is a simulation model, which implies the exploration of simulations of alternative scenarios for human and natural system developments over the long term and communicating them in a participatory setting.

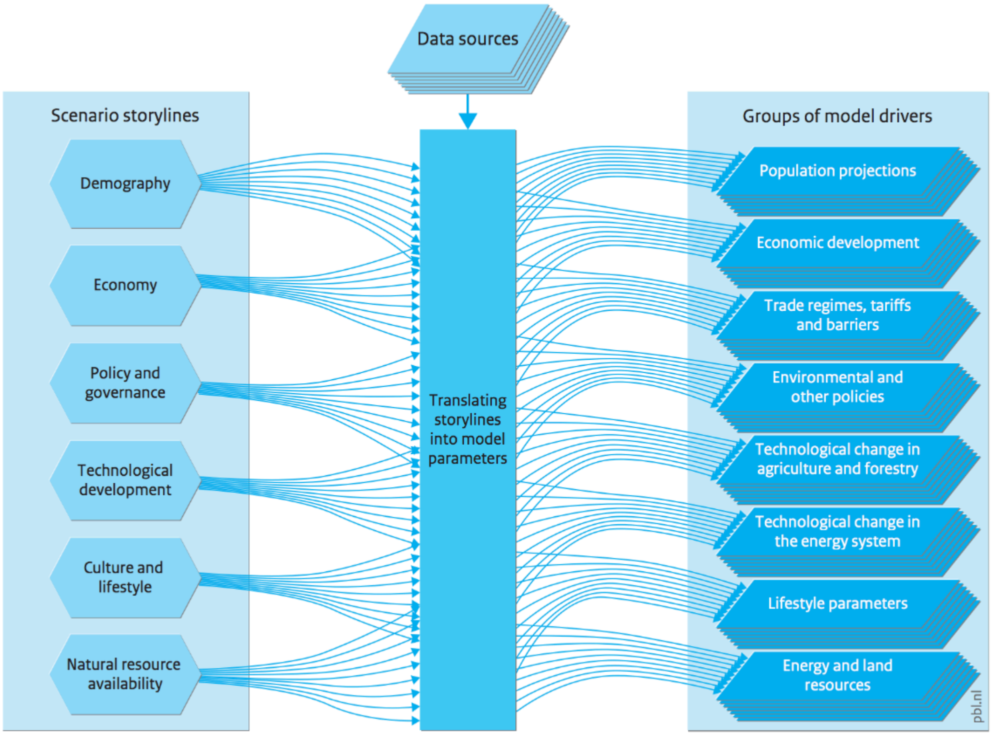
Within the family of the IAMs, IMAGE developers classify the model within the IAM typology as a *Process-oriented energy/land IAM framework*. The models of this type are of an intermediate complexity for the human and the earth systems (van Vuuren et al, 2015).

IMAGE is a global/multi-regional model. It presents 26 world regions for the socio-economic system. Structurally, the model and the its documentation are designed in line with the *DPSIR* framework (Drivers Pressures State Impact Response). There are several models integrated into the IMAGE framework: GISMO (Global Integrated Sustainability Model) – sustainable development model, GLOBIO – biodiversity model, PIK-LPJmL – land use model, TIMER (the IMAGE Regional Energy Model) – energy model, MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) – climate model.

Originally designed to assess the global effect of greenhouse gas emissions, IMAGE now covers a broad range of environmental issues beyond climate change (e.g. land-use change, biodiversity loss, modified nutrient cycles, and water scarcity). Human societies harnessing natural resources to support their development are seen as the systems that put pressure on the earth system and create environmental problems. The authors of the model formulate the uniqueness of the model in the following way: "*The unique aspect of IMAGE is that is contains a consistent description of the physical aspects of environmental change, both in the human economy (also in relation to monetary trends) and the earth system. This makes the framework well suited to analyse the impact of individual measures and combined strategies in terms of synergies and trade-offs*" (van Vuuren et al., 2015).

The plans for the further development of the IMAGE model aim to make it a useful tool for exploring complex sustainability issues and trade-offs between the human and the natural systems in the context of the SDGs agenda. The IMAGE scenario section, which is aimed at exploring potential long-term pathways for human and natural system development, contains several main storylines and drivers. There are six main scenario storylines which are translated into the model's parameters. The alternative simulation results based on these scenarios are explored.

Figure 13: IMAGE model scenario storylines



Source: Stehfest et al. (2014)

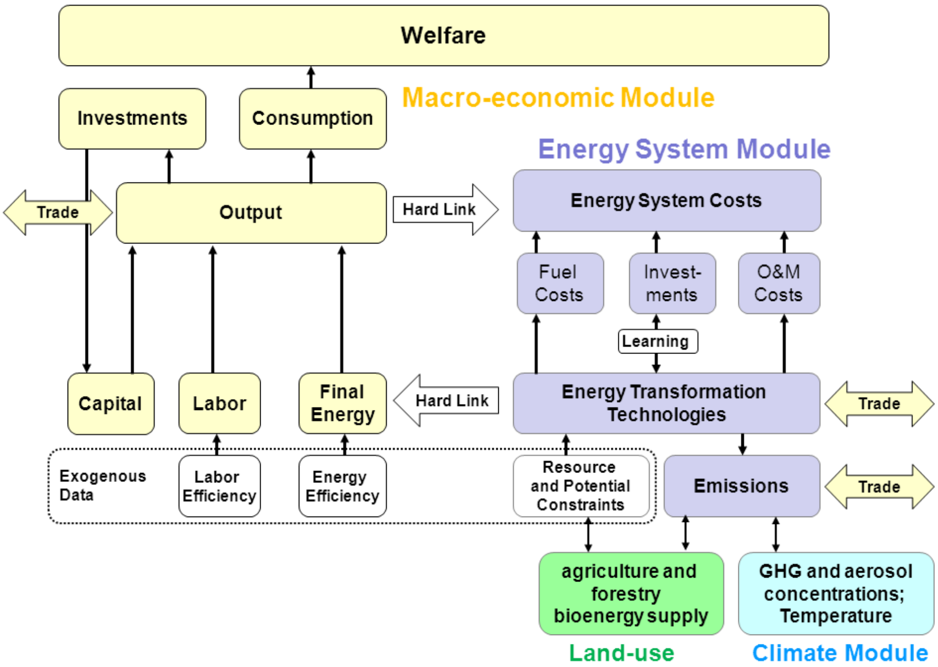
IMAGE is aimed at providing an Integrated Environmental Assessment and at being used for policy analysis. The main clients of IMAGE include the Dutch Government, the European Commission, international organizations, such as IPCC, UNEP and OECD, and the research community. In the future, efforts will be made to "*expand this client base to sector and business associations*" (van Vuuren et al., 2015).

6. REMIND-R - an Economic Growth Model

REMIND-R is a multi-regional hybrid model which incorporates an economic growth model, a detailed energy system model, and a simple climate model (Leimbach and al, 2010). The existence of interdependency between energy systems and macroeconomic systems over time is the core of REMIND-R (Bauer and al, 2009). Firstly, energy is a production factor in the macroeconomic growth model (MGM), and energy production requires financial means that are accounted for in the budget equation of the macroeconomic model. Secondly, the decision to couple the two systems is based on a "hard link"[7] approach which "*integrates the technico-economic contraints of the energy system model (ESM) into the macroeconomic growth model (MGM) as an additional set of functions and constraints and solves one very complex non-linear programming (NKP) program*" (Bauer and al, 2009, p. 97).

[7] A "soft link" approach separates the two models and integrates a reduced form model the ESM into the MGM resulting in a less complex model.

Figure 14: Structure of REMIND-R



Source: PIK (2017)

- ***The macro-economic system*** is a Ramsey-type optimal growth model in which global welfare over time is optimized subject to equilibrium constraints. It takes into account 11 world regions. Each region is modeled as a representative household with a utility function that depends upon per capita consumption.

$$U_r = \sum_t e^{-\rho t} L_{rt} \log\left(\frac{C_{rt}}{L_{rt}}\right).$$

with Population (L), consumption (C) and pure rate of time preference (ρ) of 3%. The objective of the REMIND-R model is to maximize a global welfare function that is a weighted sum of the regional utility functions:

$$W = \sum_r n_r U_r .$$

Economic output (gross domestic product, GDP) of each region is determined by a Constant Elasticity of Substitution (CES) function of the production factors, labor, capital, and end use of energy. In each region, GDP is used for consumption (C), investments into the capital stock (I), exports (X), and energy system expenditure (which consists of fuel cost (GF), investment costs (GI), and operation and maintenance cost (Go). Imports of the composite goods (M) increase GDP:

$$Y(t) - X_G(t) + M_G(t) \geq C(t) + I(t) + G_F(t) + G_I(t) + G_O(t)$$

REMIND-R follows the classical results from HOS (Heckscher-Ohlin-Samuelson) theorem and Ricardo's theory of comparative advantages. Trade between regions is induced by differences in factor endowments and technology.

All technologies are represented in the model as capacity stocks. The possibility to invest in different capital stocks provides high flexibility of technological evolution.

With its macro-economic formulation, REMIND-R is similar to the MERGE (Manne and al, 1995) and RICE (Nordhaus, Yang, 1996) models. The only difference is the high technological resolution of the energy system, and the trade relations between regions over time.

- ***The energy system model*** *(ESM)* has a detailed description of energy carriers and conversion technologies. Luderer et al (2011, p. 8) insist on the fact that ESM is embedded into the macro-economic growth model: "*the energy system can be regarded as an economic sector with a heterogeneous capital stock that demands primary energy carriers and supplies secondary energy carriers. The structure of the capital stock determines the energy related demand-supply structure. The macro-economy demands final energy as an input factor for the production of economic output. In return, the energy sector requires financial resources from the capital market that are allocated among a portfolio of alternative energy conversion technologies*".

The primary carriers include both exhaustible resources (coal, gas, oil, uranium) which are characterized by extraction costs that increase over time as cheaply accessible deposits become exhausted and renewable resources (hydro, wind, solar, geothermal and biomass) whose potential are classified into different grades, each grade is characterized by a specific capacity factor. The secondary energy carriers include electricity, heat, hydrogen, other liquids, solid fuels, gases, transport fuel petrol, and transport fuel diesel. The energy system highlights the conversion of primary energy into secondary energy carriers via specific energy conversion technology.

The distribution of energy carriers to end-use sectors forms the interface between the macro-economic model and the energy system model. REMIND-R makes a difference between the stationary end-use sector (industry and residential buildings) and end-use in the transport sector.

- ***The climate model*** is represented as a set of equations that restrict welfare optimization. The climate system takes account of the impact of greenhouse gas emissions and sulphate aerosols on the level of global mean temperature (Leimbach, 2010). The REMIND-R model has two modes for climate policy analysis: 1. A *business as usual* scenario in which the global welfare function is optimized without constraints, this is a situation where the occurrence of climate change would have no effect on the economy and the decisions of households. 2. A *climate policy* scenario, in which an additional climate policy constraint is imposed on the welfare optimization (the constraint is the limit on temperature). REMIND-R is also able to analyze the impact of carbon tax as a penalty on emissions.

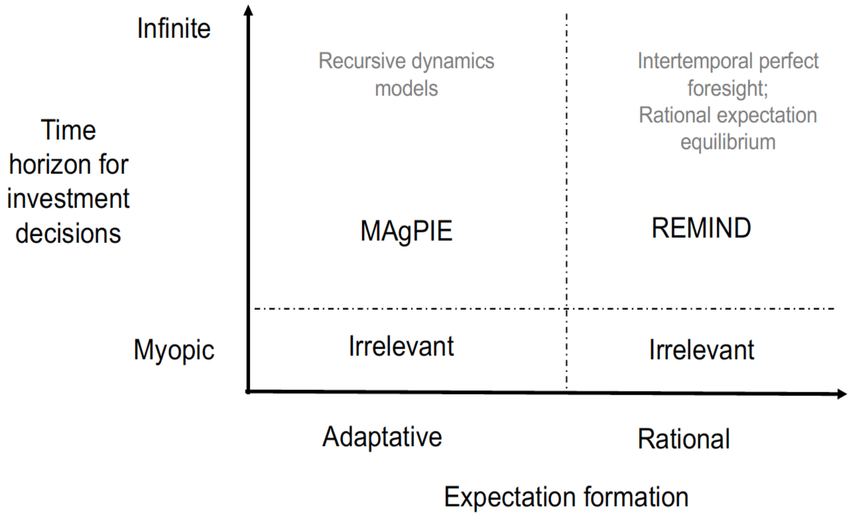
Table 1: Main characteristics of REMIND-R

key distinguishing feature	**REMIND - R**
Macro-economiccoreand solution concept	Intertemporal optimization: Ramsey-type growth model, Negishi approach for regional aggregation
Expectations/Foresight	Default: perfect foresight.
Substitution possibilities within the macro- economy / sectoral coverage	NestedCESfunctionforproductionofgenericfinalgoodfrombasic factors capital, labor, and different end-use energy types
Link between energy system and macro- economy	Economic activity determines demand; energy system costs (investments, fuel costs, operation and maintenance) are included in macro-economic budget constraint. Hard link, i.e. energy system and macro-economy are optimized jointly.
Productionfunctioninthe energy system / substitution possibilities	Linear substitution between competing technologies for secondary energy production. Supply curves for exhaustibles (cumulative extraction cost curves) as well as renewables (grades with different capacity factors) introduce convexities.
Land use	MAC curves for deforestation
International macro- economiclinkages/ Trade	Single market for all commodities (fossil fuels, final good, permits)
Implementation of climate policy targets	Pareto-optimal achievement of concentration, forcing or temperature climate policy targets under full when-flexibility. Allocation rules for distribution of emission permits among regions. Other options: Emission caps & budgets, taxes equivalent.
Technological Change / Learning	Learning by doing (LbD) for wind and solar. A global learning curve is assumed. LbD spillovers are internalized. Labor productivity and energy efficiency improvements are prescribed exogenously.
Representation of end-use sectors	Threeenergyend-usesectors:Electricityproduction,stationarynon- electric, transport
Cooperation vs. non- cooperation	Pareto: full cooperation
Discounting	Constant rate of pure time preference (3%)
Investment dynamics	Capital motion equations, vintages for energy supply technologies, adjustment costs for acceleration of capacity expansion in the energy system

Source: Luderer (2011, p. 3)

Recently, REMIND-R has been improved by work on the scenarios, expectations, and narratives. Problems applying optimization methods have been solved by using the partial equilibrium model (MAgPIE). The formation of expectations plays a key role: adaptative expectations (investors assume current princes to remain constant) vs rational expectations (investors know the models' outcome and form consistent expectations).

Figure 15: the role of expectations in REMIND-MAgPIE model



Source: Bauer (2018)

The applications of REMIND-R are interesting: 1. Analysis of decarbonization pathways in an integrated framework (interrelation of climate policy, trade, renewable resources, and mitigating climate policy), 2. Regional distribution of mitigation costs (cost distribution may be broken down into differences in domestic abatement costs, effects related to shifts in trade volumes, prices of fossil energy carriers, and financial transfers in the context of the global carbon market), 3. Exploration of very low stabilization targets (including technologies and cost reduction), 4. Analysis of best vs second-best mitigation strategies (large number of mitigation options).

7. Concluding remarks and challenges

Over the past 20 years, IAMs have succeeded in bringing together a range of international institutions (IIASA, PIK, PLB, CIRED) around the issue of economics, energy, and climate change integration. These models are distinguished both by their structural forms (key variables, scale, representations, etc) and the level of complexity of the systems studied (economic system, energy system, climate system). While the nexus economy/energy/climate constitutes the main framework of the IAMs, it does not exhaust the subject nor the future developments of IAMs. The modular structure of IAMs makes it possible to integrate other nexuses (population/agriculture/food) or (biodiversity/water/air) which are equally important for the future of our societies. Table 2 presents many components (goals, macroeconomic structure, scale, type of models) of the different IAMs discussed.

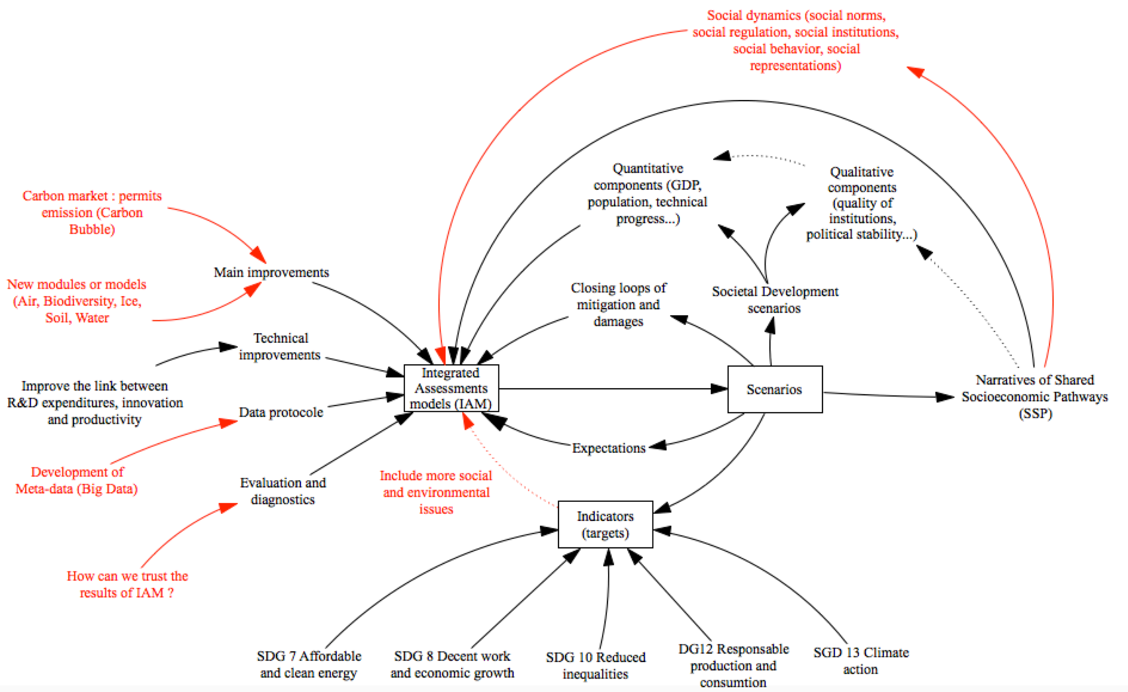
IAM	DICE	MESSAGE	IMAGE	GEM-3E	REMIND
Macroeconomic core of the model	Dynamic Optimization Model (Ramsey, 1920)	None but soft-linked to general equilibrium model MACRO	The economy is represented separately by different model components. The model is not suitable to assess detailed economic impacts, such as sector level impacts	Dynamic Optimization Model	Dynamic Optimization Model (Ramsey, 1920) Perfect foresight
Goal	Estimate the optimal GHG reduction trajectory	Medium- to long-term energy system planning and analysis of climate change policies	Exploring the long-term dynamics and impacts of global changes that result from interacting socio-economic and environmental factors	*Examine the potential for the EU to gain a first mover advantage if it adopts earlier than others ambitious GHG emissions reduction policies*	Analysis of decarbonization pathways in an integrated framework + regional distribution of mitigation costs
Scale	DICE – RICE Multiregional model	National & Multiregional models (11 regions)	Global (multi-regional)	Multiregional model (38 regions and 31 sectors)	Multiregional hybrid model (11 world regions)
Type of model	Optimization policy	Optimization policy	Simulation policy	Optimization Policy	Optimization Policy
Representation		Domestic resource utilization, energy imports and exports, trade-related monetary flows, investment requirements, types of technologies, pollutant emissions, inter-fuel substitution process	Say how and whether the transition is modelled	Economic circuit, energy technologies and GHG emissions	Trade in final goods, primary energy carriers, emissions allowance
Key variables	Energy, natural resources, income and population	Resource extraction, technology installation, technology activity	Exogenous scenario drivers (demography, policy and governance, technological development, culture and lifestyle, natural resource availability)	GDP, jobs, energy prices, consumer prices, sectoral production, budget deficit	Production, capital, labor and energy
Externalities	Carbone Cycle				
Economic System	Competitive Market Balance Intertemporal optimization of price and consumption	Supply cost minimization		Economic circuit (national account + IOT) Public sector, transport and international trade, financial sector	Economic system is hard linked to the energy system (economic activity results in demand for final energy)
Energy System	System combining market mechanisms and economic policies	Detailed description of energy supply side and technologies	TIMER energy model focusing on long-term trends in energy supply and demand	Energy efficiency and Energy technologies (coal fired… CCS (SCC?) gas)	Energy system consider exhaustible primary energy resource and renewable energy potentials
Climate System	Climate change is captured by	Only GHG emissions but	Climate model MAGICC. Emissions	Climate by GHG emissions	Carbon Cycle and temperature model

	global average temperature	linked to climate model MAGICC	beyond GHG are present	(energy and process related)	
Technology		Technological learning endogenous	Endogenously modelled technological learning. Exogenous technological progress effects.	Modelling technical progress (R&D decision)	Technological change is exogenously driven

Table 2: components of the IAMs

Today, the challenges of IAMs seem connected to the new aims of research design. The IAM framework links models, scenarios and indicators, especially Sustainable Development Goals. We can present the debate by the following diagram.

Figure 16: Model – Scenarios and Indicators issues for IAM



IAMs have to be improved, four possible key additions to IAMs may play roles: *main improvement* (carbon market introduces financial markets in the macroeconomic structure, the equilibrium between saving and investment is not realistic), *technical improvement* (knowledge of technology diffusion, learning curve, evaluation of transport costs, and cross elasticities), *data protocol* (development of spatial data exchange, big data, time series data), and *evaluation and diagnostic* of IAM.

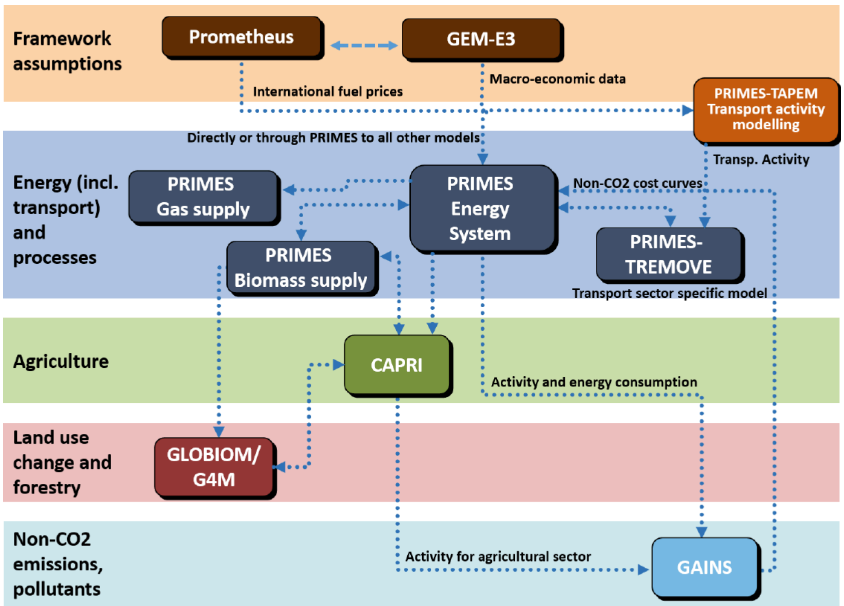
Indicators, like targets, can help to introduce more social and environmental issues - Stakeholders would fix the targets they want to reach; national policies could explain the gap between expectations and results.

Scenarios can be deduced from the structure of IAM - different scenarios give signals about trajectories and pathways. Scenarios depend on basic assumptions (implemented in the model) but are not able to anticipate the future.

Future uncertainty may be captured by different narratives - these narratives transform qualitative data into quantitative scenarios and engage modelers to propose shared socioeconomic pathways (SSP). Social dynamics (social standards, social institutions, social regulation, social behavior, social representations) may be useful to connect to the narrative of shared socioeconomic pathways and to modify behaviors (reducing energy consumption, water consumption, waste, etc).

In 2007, the Integrated Assessment Model Consortium (IAMC) was created in response to a call from the Intergovernmental Panel on Climate Change (IPCC) for a research organization to lead the integrated assessment modelling community in the development of new scenarios that could be employed by climate modelers in the development of prospective computerized model research for both the near term and long term. In the report EU reference scenario 2016 (Energy, transport and GHG emissions: trends for 2050), the European Commission used a series of interlinked models which combine technical and economic methodologies. The models were used to produce detailed projections per sector and per country. Most of them followed an approach which is based on micro-economics - they provided answers for a price-driven market equilibrium and combined engineering with economic representations for all sectors.

Figure 17: Reference Scenario for EU, trends to 2050



The PRIMES modelling suite is the core element for transport, energy, and CO2 emissions projections. The GAINS model is used for non-CO2 emissions projections.

The GLOBIOMG4M models are used for LULUCF emission and removal projections. The GE3M macroeconomic model is used for value added (GDP) projections by branch of activity. The PROMOTHEUS global energy model is deployed for forecasts of world energy prices and the CAPRI model for agriculture activity forecasts.

These models were used to provide the fossil fuel price trajectories used for the EU modelling (Prometheus), to prepare consistent sectorial value added and trade projections which match given GDP and population projections by country (GEM-3E), to provide the transport activity projections (PRIMES – TAPEM), to provide the energy system projection for demand and supply side sectors included full energy balance, investment costs, prices and related CO2 emissions per country (PRIMES energy system model), to provide detailed forecasts for changes in the entire transport sector in terms of transport activity by mode and transport means (PRIMES – TREMOVE), to provide the supply and transformation projections of biomass / waste resources (PRIMES – biomass supply), to provide forecasts for gas imports by country of origin (PRIMES - gas supply), to provide an agricultural forecast (especially for livestock and fertilizers use (CAPRI)), to provide non-CO2 GHG and air pollutant emissions (GAINS), and to include the changes in land use and related CO2 emissions (GLOBIOM/G4M). If these models provide background information for international climate policy negotiations, they have started more debate about the evaluation of IAMs or trust in their results, especially when they are used to explain open and complex systems.

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5. Paper IV: Steady state of energy: Feedbacks and leverages for promoting or preventing sustainable energy system development

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Steady state of energy: Feedbacks and leverages for promoting or preventing sustainable energy system development

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ABSTRACT

While energy demand has been growing over the last few decades and is projected to keep expanding, the current energy system is pushing biophysical source and sink limits. At the same time, growing demand for energy globally is associated with an expansion of welfare. To avoid undesired environmental and social implications of energy developments in the long run, a systemic understanding of the dynamics promoting or preventing sustainable energy development is needed. Departing from Daly's steady state economics theory, this study conceptualizes a sustainable energy system using a systems thinking approach. Efficiency increase, the central element of Daly's theory, defined as the service/throughput ratio, is put in the center of a conceptual analysis of a sustainable energy system and is carefully scrutinized. Meadows' leverage points concept is used to facilitate an analysis of different policies that aim at promoting sustainable energy system development. This study concludes that energy policies always need to be explored as part of the broader causality structure into which they are embedded. Otherwise, their impacts on other variables in the system may be overlooked, such as in the case of efficiency increase, which is shown to have undesired side effects for the development of a sustainable energy system.

1. Introduction

The energy system interacts with economic, social and environmental systems and shapes their development. Thereby, it directly and indirectly affects many of the sustainable development goals (SDGs) (e.g. (Najam and Cleveland, 2003; Vera and Langlois, 2007). Despite environmental limits being under discussion for more than four decades, our socio-economic system is still moving towards and beyond planetary limits (e.g. Meadows et al., 1972; Rockström et al., 2009; Steffen et al., 2015). One of the main reasons for this has been the expansion of the current energy system, which is fossil-fuel-based (Steffen et al., 2005). Although earlier impacts of human beings are observable, none of the changes before (e.g. change in the agricultural system) their widespread utilization caused such a significant impact on the earth's climate (Steffen et al., 2005).

Many studies (e.g. Campbell and Laherrère, 1998; Simmons, 2011; JRC, 2013; Seppelt et al., 2014; WWF, 2014) on possible energy futures have focused on the resource limits of the current energy system, especially those of non-renewable resources. Fossil fuels have been a particular focus, for example, in the peak oil debate or the potential of new sources, such as shale gas or tar sands (e.g. Nashawi et al., 2010) as well as nuclear energy (e.g. OECD/NEA and IAEA, 2014).

Currently a renewable based energy system is increasingly coming into focus as a solution to resource limits and climate change. Renewables represent a core element in future energy pathways (e.g. IIASA, 2012; IEA, 2014). However, renewables cannot be exploited in an unlimited manner, as either their regeneration rate and intermittency pose a limit, or the resources (i.e. rare earth metals) needed for current technologies to harvest or use renewable energy are limited (de Vries et al., 2007; Tao et al., 2011; Davidsson et al., 2014).

Although it is essential to understand the implications of resource limits, limits with regards to the sink capacity are equally important to be considered when dealing with the development of the energy system. Sink limits determine how much more pollution and waste can be absorbed by the environment without causing any long-term environmental damage. Therefore, sink limits are also accounted for when analyzing current and future energy systems (e.g. Steffen et al., 2005; van der Zwaan and Gerlagh, 2006; Kesicki and Anandarajah, 2011; Pachauri et al., 2014).

Growing demand for energy to support an expanding economy is pushing against the discussed biophysical source and sink limits (e.g. Boulding, 1966; Meadows et al., 1972; Rockström et al., 2009; Steffen

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et al., 2015). An argument often brought forward in this discussion is that economic growth facilitates human development, poverty reduction and increases welfare. However, the results of studies examining the connection between energy consumption and living standards (e.g. Mazur and Rosa, 1974; Rosa, 1997; Pasternak, 2000; IEA, 2004; Steinberger and Roberts, 2010) confirm that in fact after a certain threshold of primary energy consumption has been reached, human development does not improve anymore, as measured by the Human Development Index (HDI).

It appears that a steady level of consumption of high quality energy is sufficient to achieve development as measured by the HDI. This result holds for two of HDI´s sub-components: literacy rate and life expectancy (Steinberger and Roberts, 2010). According to Steinberger and Roberts (2010), the only parameter often used to measure socio-economic development, which does not stay constant after a certain energy threshold has been reached, is GDP as that does not have a maximum value. However, an argument often brought forward is that the relevant measure for assessing the relationship between energy and GDP is energy intensity. In this case energy intensity refers to energy consumed per dollar of GDP created (Banks, 2000). Therefore, decoupling of GDP and energy consumption is proposed in order to stay within environmental limits, while at the same time maintaining the benefits of economic growth (Jackson, 2016). However, GDP has been highly criticized as a socio-economic indicator, questioning the desirability and feasibility of an ever-growing economy. Alternative economic concepts, such as those focused on degrowth (e.g. Schneider et al., 2010; Kallis, 2011; Victor, 2012) and steady state economics (e.g. Daly, 2011; O'Neill, 2012; García-Olivares and Ballabrera-Poy, 2015) challenge the existing economic model and design visions of a long-term, sustainable socio-economic system. John Stuart Mill wrote about the stationary state in the middle of the 19th century from a purely biophysical perspective (O'Neill, 2012). However, Daly was among the first economists in the 20th century who dealt with environmental limits from a macroeconomic perspective. This, and the fact that much of the later work and discussions related to Daly's steady state concept (e.g. Kerschner, 2010, O'Neill, 2012) and degrowth, as well as sustainability, are the reasons for choosing the steady state concept as a point of departure for this study.

Due to the fact that energy appears to represent a major link between human development and the environment, it is at the center of this analysis. Departing from the assumption that an ever-growing energy system appears to be impossible due to biophysical limits, this paper seeks to develop a vision of a steady state of energy based on Daly's steady state economy concept. The goal is to answer the following research questions:

- To what extent can a steady state approach help conceptualize a sustainable energy system?
- What leverages can be identified to achieve a sustainable energy system?
- What are the implications of using the steady state theory for a sustainable energy system at global and national policy levels?

In order to answer these research questions, a dynamic analysis of parts of Daly's theory is conducted and translated into energy terms. This is done using Causal Loop Diagrams (CLDs), described in the Methods section. Once the steady state of energy has been conceptualized in this manner, leverage points are identified and analysed with regards to their effectiveness in delivering a sustainable energy system. This is followed by some concluding remarks.

2. Methodological approach

The method chosen for carrying out the conceptual analysis is system dynamics. One of the tools used in system dynamics are Causal Loop Diagrams (CLDs). Causal loop diagrams, among other tools in System Dynamics, are used to reveal the feedback structure of systems. Schaffernicht (2010) refers to CLD´s as “qualitative diagramming language for representing feedback-driven systems”. Within CLD´s all the variables inside the system's boundaries are mapped. Causal links between individual variables are depicted by arrows. These links can have positive (+) or negative (-) polarity, which are referred to as link polarities. The term positive or negative link does not say whether it is good or bad, but simply provides a description of the bi-causal relationships between variables. A positive link is one in which the causing variable and affected variable change in the same direction. Hence, an increase in the cause leads to an increase in the effect, and a decrease in the cause leads to a decrease in the effect. Fig. 1

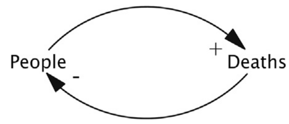

Fig. 1. Example of a CLD.

In more concrete terms, this means that the diagram below can say the following:

1. More people lead to more deaths and more deaths lead to less people.
2. Less people lead to less deaths and less deaths lead to more people.

Causal links only represent the structure of a system, not the behavior generated by the structure. Thus, they explain what would happen if the independent variable increases or what would happen if it decreases. When assigning polarities between two variables, other variables are assumed to be left aside, and only the causal relationship between those two variables is determined.

If several variables of the system are linked in a unidirectional manner, in which the starting point matches the end point, it is called a causal loop. Polarities of causal links between variables within this loop define the dynamics of it. When a loop has a positive polarity, it has a reinforcing effect (labelled R in the CLD), and when it has a negative one it is termed balancing (labelled B in the CLD). One variable can be linked, as a cause and/or an effect, to several variables, which makes it possible for several loops to be linked as well. Unlike other tools of system dynamics, CLDs usually do not distinguish between stock and flow variables (Sterman, 2000). However, through mapping the dynamics, structure and feedbacks of a system with CLDs it becomes possible to investigate its behavior and arising trade-offs between different goals and interventions in more detail (Sterman, 2000).

3. Conceptualizing a steady state of energy

According to Daly, “A steady-state economy is defined by constant stocks of physical wealth (artifacts) and a constant population, each maintained at some chosen, desirable level by a low rate of throughput (Daly, 1974: 15). The main focus of analysis in this paper is the second part, which revolves around increasing efficiency. Daly states that ”progress in the steady state consists in increasing ultimate efficiency in two ways: by maintaining the stock with less throughput and by getting more service per unit of time from the same stock”. In this theory, the author distinguishes between physical stocks and the stock of physical wealth. The relationship between efficiency, service, throughput and stocks is explained in the following equation:

$$\textit{Ultimate Efficiency} = \frac{\textit{Service}}{\textit{Throughput}} = \frac{\textit{Service}}{\textit{Stock}} \times \frac{\textit{Stock}}{\textit{Throughput}}$$

Displaying Daly's equation in the CLD (Fig. 2) shows that one reinforcing loop is connected to two balancing loops.

Applying Daly's equation to the energy system means decreasing the

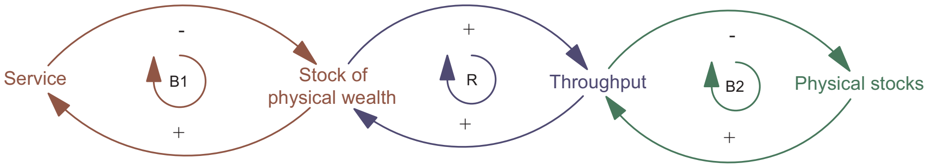

Fig. 2. CLD of Daly's equation.

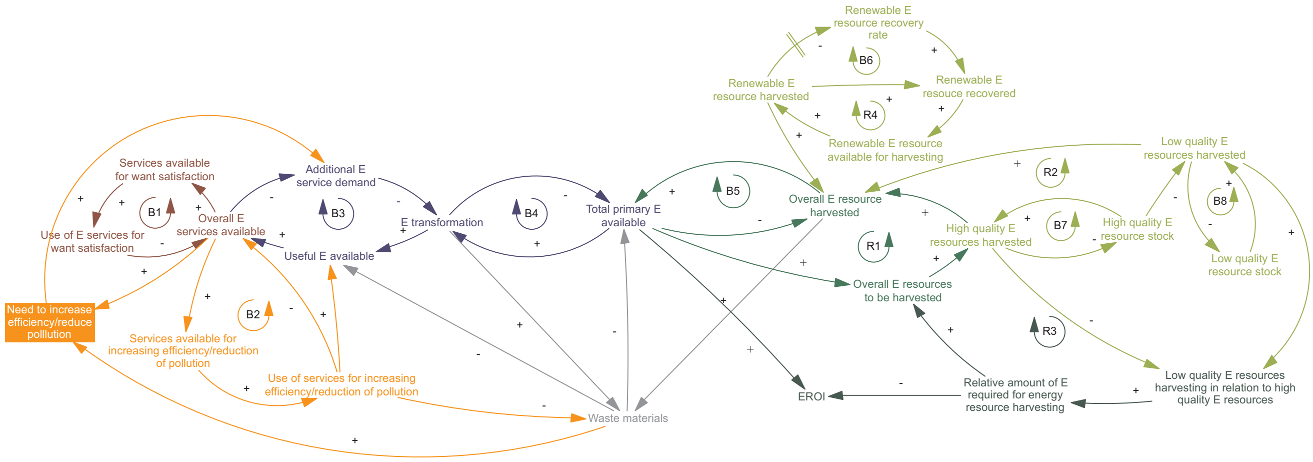

Fig. 3. CLD of steady state of energy based on Daly's equation.

energy resources used per energy service. In order to facilitate a dynamic analysis on a potential steady state of energy, the elements of the equation are translated into energy system terms. This is shown in Fig. 3 and will be described in the following.[1]

The CLD in Fig. 3 portrays the dynamic interaction between the three main sectors of the energy system: (i) energy services use (red sector), (ii) energy services creation (blue sector), and (iii) energy resource harvesting supporting energy services creation (green). Although the CLD in Fig. 3 contains many more variables and dynamic interactions between them than the one in Fig. 2, both CLDs share the same underlying structure, which portrays the process of creating useful services for society though natural resource harvesting and transformation.

Starting at the basis of Daly's equation, physical stock, is what can be referred to as all energy resources in the energy system. They represent technical potential resources, which are technically feasible to recover, independent of their economic feasibility. This includes non-renewable and renewable as well as high-quality and low-quality resources (Mercure and Salas, 2012).

Renewables need to be differentiated between flow-based ones, which in principle are unlimited and do not depend on any kind of recovery (e.g. solar, wind, hydro), and stock-based ones, which need time to recover and can only be used sustainably if the harvesting rate is below the recovery rate (e.g. bio-energy, geothermal). The harvesting technology of some flow-based renewables (solar photovoltaics and wind) currently depends on scarce materials (e.g. Nd, copper), which possibly limits their harvesting potential in the long run (e.g. Skirrow et al., 2013; WWF, 2014; Dewulf et al., 2016).

It is possible to distinguish between high-quality and low-quality energy. High-quality energy, such as electrical energy, has a high exergy content (i.e. usable energy). Low quality energy, such as district heating, has a low exergy content (Dincer, 2002). This distinction refers to the quality of energy at the stage of final energy consumption. However, resources can also be defined in accordance with their quality. This is especially relevant for non-renewable resources, as their quality tends to decrease. Fossil fuels generally count as high-quality fuel, and their quality extends from worst to best (i.e. higher usable energy contents to lower usable energy contents - also see Energy Return on Investment (EROI) discussion below).

In general, according to the best-first principle, the best high-quality resources are harvested first (i.e. interaction between loops R1, B7, B8 in Fig. 3). In this paper, renewable resources, although often harvested at comparably low efficiency rates, therefore counting as low-quality resources, are still considered to be desirable to utilize when they are transformed into high-quality energy. Although their harvesting efficiency also decreases (see EROI discussion) with the growing number of installations, their harvesting at lower efficiency rates does not increase pollution or waste products. In this paper, low-quality fuels refer to traditional fuels, such as traditional biomass, charcoal and dung, (see Goldemberg and Teixeira Coelho, 2004). They make up a large share of the primary energy used in developing countries.

Since the usable energy content of low-quality fuels and lower quality high-quality fuels is lower, more primary resources are needed to provide the same amount of useful energy, which ultimately translates into energy services, than would be needed if a high-quality resource would be used. This also relates to Daly's (1974) point of decreasing quality of physical stocks and therefore increasing entropy of resources used, ultimately leading to more pollution and waste. As the best high-quality fuels become scarcer, increasingly lower quality ones are used (e.g. coal of lower quality, shale gas), and thereby overall more energy resources are required. This is also reflected in decreasing EROI, which has been reducing considerably for oil and coal over the last decades (Cleveland et al., 1984; García-Olivares et al., 2012; Jefferson, 2014). A similar effect can be observed for renewables, when looking at the locations of power plants reliant on renewable energy. Locations where there is a high rate of harvesting potential (e.g. high wind speeds) are chosen first and those of lesser potential utilized later (e.g. Moriarty and Honnery, 2016). The choice between high- and low-quality energy resources can be translated into a decrease in EROI. An increase of low-quality energy resources harvested adds to the total amount of energy resources to be harvested and, eventually, to a total amount of energy needed to support harvesting of low-quality energy resources (i.e. dark-green structure including loop R3 in Fig. 3). The

[1] This analysis of the steady state dynamics of the energy system excludes any external drivers, such as population growth and the rebound effect.

two balancing loops for the low-quality and high-quality resources (i.e. loops B7, B8 in Fig. 3) and the overall resources harvested are in line with the balancing loop between physical stocks and throughput of Daly's equation. Although differentiating between low- and high-quality fuel adds additional causal loop structure (i.e. light-green structure in Fig. 3), the overall balancing effect stays the same: the more resources that have been harvested, the less resources that are available; as well as the more resources that are available, the more that are harvested.

As Daly defines the entire process from resource harvesting to the creation of physical wealth (e.g. infrastructure), as well as the related waste and pollution as throughput, this includes several feedback structures in the energy system. Throughput is needed to build up physical wealth and maintain it (Daly, 1974). The more physical wealth that is created (e.g. housing heating systems), the more throughput (energy conversion for heat) is required to maintain it.

Starting at the initial level of throughput, harvesting, a simple balancing loop comes into play. The more primary energy that is available, the less that needs to be harvested (i.e. loop B5 in Fig. 3). However, this balancing loop is connected to another balancing loop of the throughput process, which creates an overall reinforcing behavior (i.e. combination of loops B3 and B4 in Fig. 2). This reflects the reinforcing behavior in the small CLD (i.e. loop R in Fig. 2). The more primary energy that is available, the more that gets transformed. Similarly, the more primary energy that is transformed, the less primary energy that is available (i.e. loop B4 in Fig. 3). This again leads to additional resource harvesting.

The discussed reinforcing behavior associated with resource harvesting is connected to a balancing structure. The latter stems from the fact that the more services that are available, the lower is additional service demand, which then again means less energy transformation would have to take place (i.e. loop B3 in Fig. 3). This behavior is only present in a system without external drivers of energy demand growth and does not account for the rebound effect (see review of definitions in (Sorrell and Dimitropoulos, 2008), and both of those factors are excluded from this analysis.

Another aspect of the throughput process are the waste materials, which in this case refer to solid waste as well as dispersed pollution. With the expansion of overall harvesting and transformation processes, waste materials build up (i.e. grey part in Fig. 3). The more waste materials occur during the harvesting and transformation processes; the more energy conversion losses increase, which actually translates into less useful energy available. Waste materials increase as the quality of the resources decrease, since higher entropy resources mean less energy content in the primary sources, which results in a need for more primary sources and more waste materials.

The last part of the CLD (Fig. 3), which matches the small CLD (Fig. 2) showing Daly's equation, is the energy service. As in the CLD representing the equation, the energy service loop is a balancing one (i.e. loop B1 in Fig. 2), which connects to throughput. Daly argues that services are created from a stock of wealth, which in the case of energy is useful energy. An energy service can be defined as “actual utility gained by using useful energy: a brightly illuminated working space, refrigerated food, clean laundry, transportation of goods from one place to another, etc. The quantity of energy used is irrelevant to the value of the energy service (e.g. the quality of lighting is important, not the electricity consumed, transportation to the destination is decisive, not the petrol consumed)” (German Advisory Council on Global Change, 2003). The more energy services are available, the more services are satisfied and less additional services are needed (i.e. loop B1 in Fig. 3). However, through using energy services, less energy services are available and more additional services are required, which means more useful energy needs to be generated. This is in line with Daly's argument that every throughput needs first to be accumulated in a stock of physical wealth, i.e. useful energy, before the service can be used.

The additional structure that has been added to the CLD (i.e. grey part in Fig. 3) is not visible in the small CLD (Fig. 2) because pollution is integrated into the overall throughput. Additionally, the aspect of increasing efficiency has been explicitly added as a dynamic structure (i.e. orange part in Fig. 3). It might appear more obvious that measures for reducing waste and pollution and thereby making the energy system more environmentally friendly necessitates additional energy, since pollution reduction is related to some kind of energy service. At the same time, the fact that an increase in energy efficiency leads to an additional demand on energy services to increase efficiency (e.g. construction of more efficient cars) might be less evident.

Waste and pollution reduction services, as well as services that increase efficiency, draw from the overall available useful energy (i.e. loop B2 in Fig. 3). Thereby, they reduce the energy services available for want satisfaction. This means more useful energy is required to maintain a steady level of energy services for want satisfaction, as well as allows for energy efficiency increase, and waste and pollution reduction measures. Hence, greater energy efficiency and environmental regeneration, as well as pollution and waste reduction, might for a period of time even increase energy demand, which translates into higher resource demand and more waste materials, and destabilizes rather than stabilizes the energy system.

The dynamic conceptualization of the steady state shows that keeping the service-throughput-stock relationship within biophysical boundaries, by keeping it at a constant or continuously decreasing level, is a difficult task and increasing efficiency might not be the right instrument for this endeavor. However, through dynamic conceptualization it became possible to analyze one of the main focuses of the steady state, which is energy efficiency, and identify several other leverages to achieve a sustainable energy system.

4. Leverage points

There are multiple goals, including biophysical and socio-economic goals, which future energy systems need to satisfy in order to be in line with trajectories towards sustainable development (IIASA, 2012; Pachauri et al., 2014). Therefore, it is important to have a clear understanding of the kind of energy system that would satisfy those goals. Having such understanding could help defining clear and feasible transition paths from existing energy systems to desired versions, and identifying the main leverage points to making changes happen can support this process.

In line with Daly's overall steady state concept, the steady state of energy can be defined as maximizing energy services, while minimizing energy input to help achieve the longest lasting energy system. By conceptualizing the steady state of an energy system in a dynamic manner and applying the leverage point concept, currently applied and potential strategies for reaching a sustainable energy system are explored.

This section of the paper builds on the CLD presented in Fig. 3, where the dynamics between the main elements of the steady state of energy were explored. In her concept of the 12 leverage points, Meadows (1997) identifies places to intervene in complex systems. Applying this concept, the leverages that can be seen as main intervention points for reaching a steady state of an energy system are discussed.

According to Meadows, there are 12 different categories of leverage points, which differ according to the level of their impact - from the lowest to the highest.

These leverages are as follows (Meadows, 1997):
(in increasing order of effectiveness)

12) Constants, parameters, numbers
11) The sizes of buffers and other stabilizing stocks, relative to their flows
10) The structure of material stocks and flows
9) The lengths of delays, relative to the rate of system change

8) The strength of negative feedback loops, relative to the impacts they are trying to correct against
7) The gain around driving positive feedback loops
6) The structure of information flows
5) The rules of the system
4) The power to add, change, evolve, or self-organize system structure
3) The goals of the system
2) The mindset or paradigm out of which the system — its goals, structure, rules, delays, parameters — arises
1) The power to transcend paradigms.

In this study, only 6 leverages out of 12 are investigated. Selected leverages are considered the most relevant for the steady state of energy analysis based on the CLD of the conceptual analysis of the steady state of energy dynamics. Hence, the leverage points that are discussed are only those that can be deduced from the CLD presented above (Fig. 3). Therefore, a number of leverage points are not addressed. The excluded leverages include the ones that relate to stock-and-flow structures, as they were not explicitly dealt with in this analysis (leverages 11 and 10). Additionally, there are leverages which require quantitative analysis in order to assess their impact, e.g. strength of the loops (leverages 8 and 7). The last group of leverages excluded from the analysis cannot be discussed within the boundaries of this study since they require specific details on institutional and actors' power (leverages 5 and 4).

The discussion of the leverage points begins with the leverages with lowest impact and moves on to those with highest impact. One of the most frequently advocated and picked up aspects of the steady state concept, i.e. efficiency, appears to be a leverage of low impact. Below, the selected leverage points are discussed in detail.

4.1. Leverage 12. Constants, parameters, numbers

The CLD in Fig. 4 is based on the CLD in Fig. 3. It pictures in more detail the sectors of energy service creation and use, and in less detail the sector of energy resource harvesting. The goal of this CLD is to explore the dynamics of energy efficiency in the process of energy services creation and use.

Energy efficiency increase is normally considered one of the key parameters for achieving a sustainable state of the energy system (e.g. United Nations, 2007; IRENA, 2015; World Energy Council, 2016). This is, for example, represented in the EU Energy Roadmap 2050 within the European Energy Strategy and Energy Union (European Commission, 2011). The idea of maximizing energy efficiency corresponds to the ultimate efficiency originating from Daly's theory of the Steady State (Daly, 1974). According to this theory, increasing ultimate efficiency aims at minimizing resource throughput and maximizing the amount of produced services at the same time.

Using the CLD presented in the previous section (Fig. 3), as an illustrative and analytical tool, the effect of an increase in energy efficiency on the steady state of the energy system is explored (Fig. 4). It shows that maximizing energy efficiency leads to two main dynamic effects: (1) decreasing energy-related resource waste and conversion losses (i.e. loop B1 in Fig. 4) (2) increased harvesting of natural resources (i.e. loops B3, B4, B5 in Fig. 4). The latter effect does not derive directly from an energy efficiency increase but rather indirectly: the need to increase energy efficiency leads to an increase in demand for energy services to support energy efficiency measures, which, in turn, requires harvesting of natural resources to build the service-supporting capacities. Thereby, this dynamic effect is the same as the one derived from Daly's steady state equation described above (Fig. 2). While the first effect is intuitive and desirable, the second one is counter-intuitive and not desirable, since it creates additional pressure on the biophysical system.

As was discussed, gaining an increase in energy efficiency is connected to creating additional energy efficiency-related services which are not part of the energy services for individual want satisfaction, but an additional amount of services needed only for realizing energy efficiency gaining measures. Thus, maximizing energy efficiency alone cannot serve as a powerful leverage for reaching the steady state of an

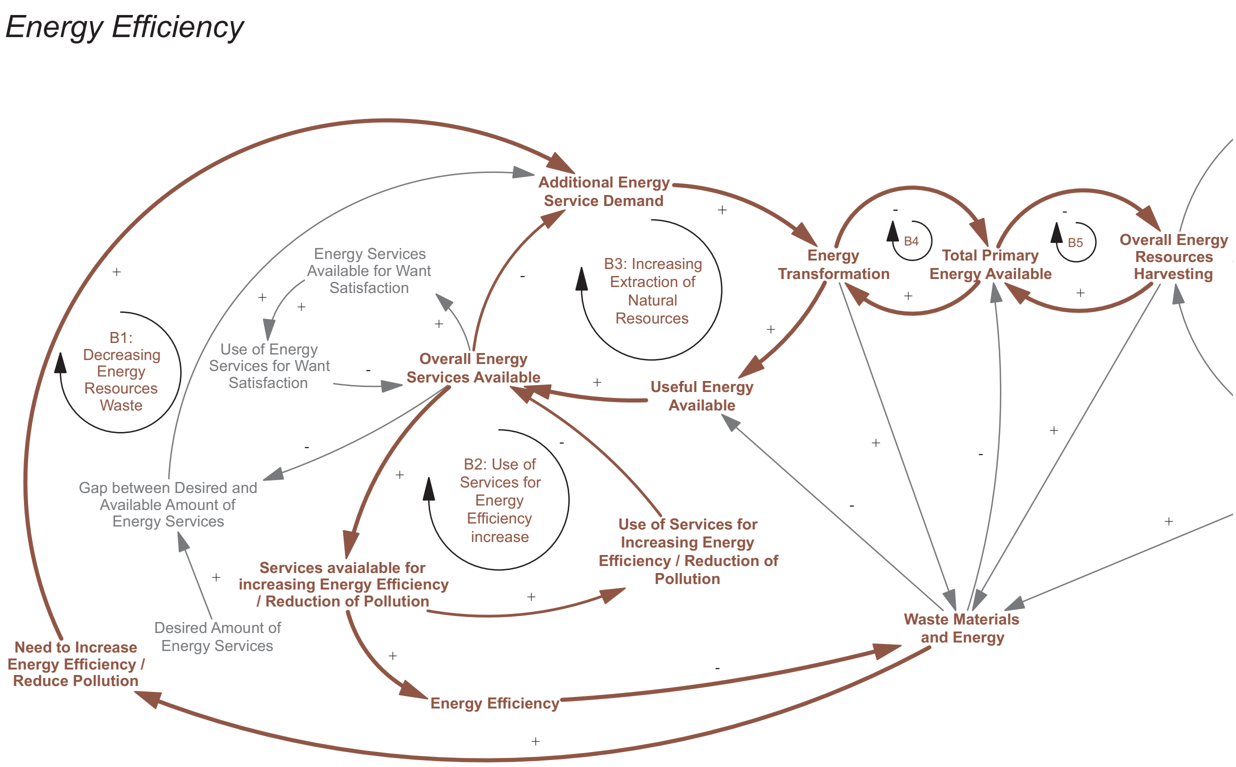

Fig. 4. Energy efficiency leverage point.

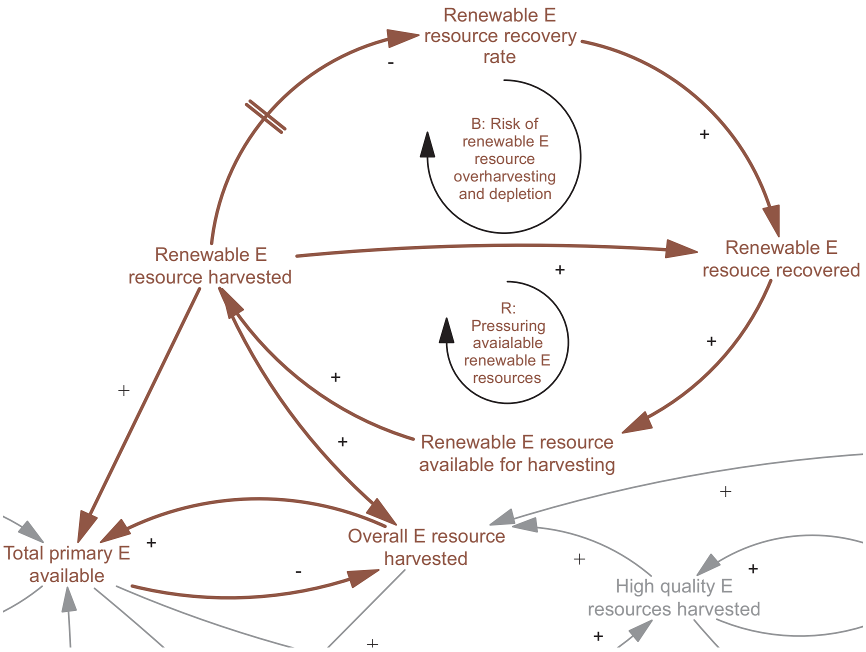

Fig. 5. Shifting to renewable energy sources leverage point.

energy system in the long run because of its controversial effects on the dynamics of the explored system, even when the rebound effect is not considered. This argument is in line with Meadows' statement that setting parameters as the systems' goals can be misleading, because although they can help with minor adjustments they can rarely change undesired behaviors of the systems.

4.2. Leverage 9. The lengths of delays, relative to the rate of system change

Energy systems are associated with multiple delays related to both natural and capital stocks. Natural system delays, in turn, are associated with energy system impacts that can be divided into source and sink capacity types (Quéré et al., 2009).

4.3. Leverage 9.a. Shifting to renewable energy sources

The CLD in Fig. 5 zooms in on the energy resource harvesting sector from the original CLD in Fig. 3., picturing the dynamics of renewable energy resource use.

It is argued in this section of the paper that the discussion on the energy system's delays needs to be considered in the context of shifting to renewable energy sources, which is promoted as one of the main strategies for sustainable energy system development at the national and international levels (compare European Commission 2011; IIASA, 2012; IEA 2014). The EU implemented legally binding targets for renewable energy in the Directive 2009/28/EC. Since then the share of renewable energy in the EU has highly increased (Eurostat, 2015).

The most crucial delays associated with source capacities of natural resource stocks have to do with the time of harvesting energy resources and the time for stocks to recover (Speirs et al., 2015) (i.e. loop B in Fig. 5). As was mentioned in the previous part, the distinction between non-renewable and renewable stems from the differences in resource recovery times.

According to the leverage points framework, shifting from the use of fossil fuel energy to renewable energy would affect the length of delays in the system. When the rate of renewable resources harvesting is equal or lower to the rate of their recovery, the depletion of energy resource stocks stops. Thus, by shifting from fossil fuels to renewable energy, provided there is no overharvesting, the pressure on the biophysical system is reduced. However, as stated before, renewable energies are subject to constraints and these can limit their potential (e.g. Buchert et al., 2009).

Regarding the overall transition from the fossil-fuel-based energy system to a renewable one, there are several main differences between renewable energy and fossil fuels that are relevant in the context of the aim of this paper. Renewable energy sources have lower efficiency than fossil fuels and relatively low EROI (Murphy and Hall, 2011). This means that when providing the same amount of energy services, more natural resources need to be used (i.e. loop R in Fig. 5). The latter would not be a problem, if all renewable energy technologies were flow-based and did not depend on harvesting raw materials. Since this is not the case, and renewable energy technologies depend on extraction of minerals in addition to land use demands, shifts to renewable energy can be associated with considerable material throughput. However, it should be noted that the amount of generated pollution caused by the use of renewable energy is much lower than pollution from fossil fuels, assuming the same amount of natural resources used (IEA 2014).

Shifting to a 100% renewable energy system means building large amounts of infrastructure for renewable energy production. The required energy for building this system will need to come from the already available energy generation capacities, which are mainly fossil-fuel-based (Hall et al., 2014). Taking all of this into account, a transition to a 100% renewable energy system may lead to an increase in pollution and material throughput in the short run, and thus the positive effects of a renewable-based energy system may be delayed in time.

4.4. Leverage 9.b. Pollution and waste material reduction

Waste generated by the energy system at different stages, from energy resource harvesting to energy service use, is part of the throughput that needs to be minimized in a steady state energy system. Waste accumulated in the natural system can be seen as a delay occurring when the rate of its generation exceeds the rate of its absorption by natural systems (CIFOR, 2003). GHG emissions accumulating in the atmosphere are a subset of the total waste generated by the energy system. Since changing the rates of pollution absorption by the natural system is possible only to some extent, decreasing the rate of pollutant emissions becomes the key leverage for minimizing waste and pollution.

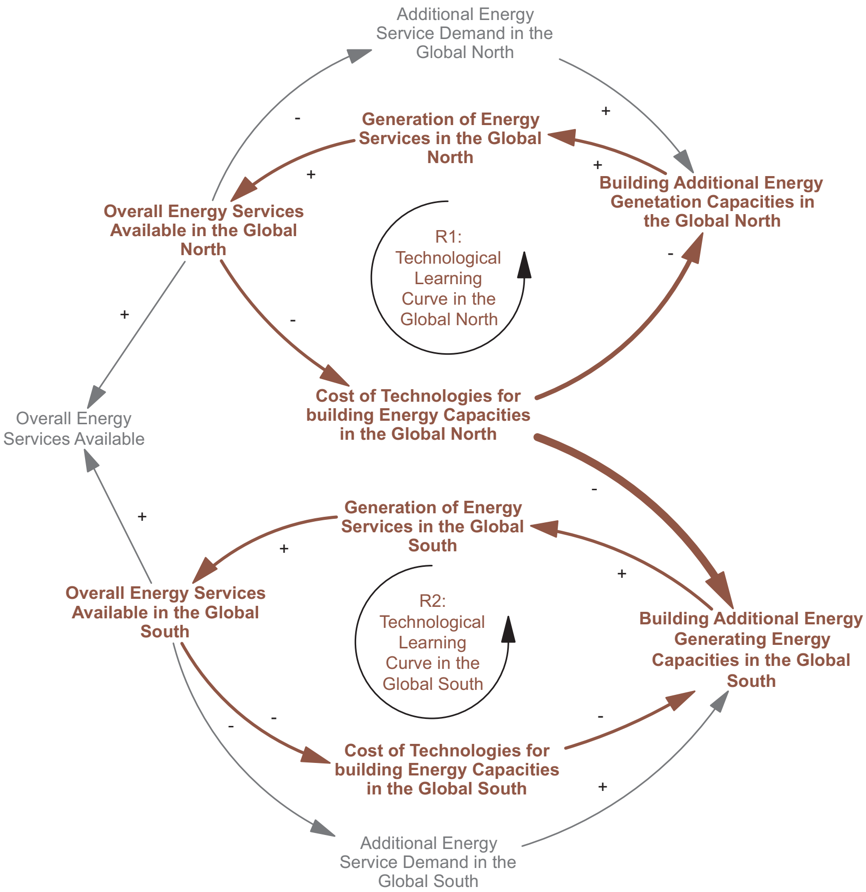

Fig. 6. Technological transfer leverage point.

For example, reducing GHG emissions that can result from the transition from fossil fuels to renewable energy is one of the clearest examples of this leverage point in action. However, pollution reduction measures, similar to efficiency measures, take from the overall stock of energy services available, and therefore an additional service demand is created. This additional service demand leads to increased resource harvesting in order to be able to provide the required useful energy for the necessary energy services. Thus, an immediate action to reduce pollution and material flows is constrained by time delays for building efficiency service capacities, as well as by the additional demand on natural resources for building such capacities.

4.5. Leverage 6. The structure of information flows

4.5.1. Technological Transfer

The CLD in the Fig. 6 portrays the dynamics of technological transfer between the Global North and Global South for providing energy services. It can be seen as a zoom of the energy services creation sector in the CLD in Fig. 3.

Energy-related technologies are the key information flow existing in the energy system. Energy technological transfer as a system leverage is based on the fact that there is inequality in access to energy services and affordability between the Global North and Global South (IIASA, 2012). Considering that the Global North already has enough energy service generating capacities, the technological learning curve effect (e.g. McDonald and Schrattenholzer, 2001) makes building additional energy service generating capacities cheaper and faster (e.g. Husar and Best, 2013) (i.e. loop R1 in Fig. 6). In the CLD presented above (Fig. 6), the overall energy services structure of the main CLD (Fig. 3) is disaggregated into the energy services available in the Global North and energy services available in the Global South. This is done in order to show the beneficial reinforcing effects of technological transfer from the more developed Global North to the less developed Global South, which leads to an increase of energy services availability in the Global South (i.e. loop R2 in Fig. 6). The Clean Development Mechanism (CDM), designed as a part of the Kyoto Protocol, is an example of a policy instrument aimed at facilitating technological transfer between the Global North and Global South (UNFCCC, 2010).

The same pattern of technological transfer applies not only to the supply side but also to demand side technologies, for example, more energy efficient appliances. This would eventually lead to achieving a global steady state of energy system, provided there is no destabilizing biophysical pressure from the energy services growth in the Global North.

The CLD in Fig. 7 pictures the energy resource harvesting sector from the CLD in Fig. 3, exploring the dynamics between high-quality and low-quality energy resource harvesting from a new angle.

Shifting from using low-quality to high-quality energy resources, the principle of which was discussed above, is another example of the information flow leverage. In Fig. 7, the prioritization of high-quality energy use is added as an additional variable to the original low and high-quality energy resources feedback structure (Fig. 3). It is implied that prioritization of high-quality energy over low-quality energy would influence decision-making when selecting between low-quality and high-quality energy resources. The latter would mean changing the structure of material flows. However, this shift is put forward within the information flow leverage point. This is done to emphasize the possible impact of prioritizing high-quality energy over low-quality options, regardless of potential technological or economic barriers (for conceptual analysis of potential barriers see e.g. Verbruggen et al., 2010).

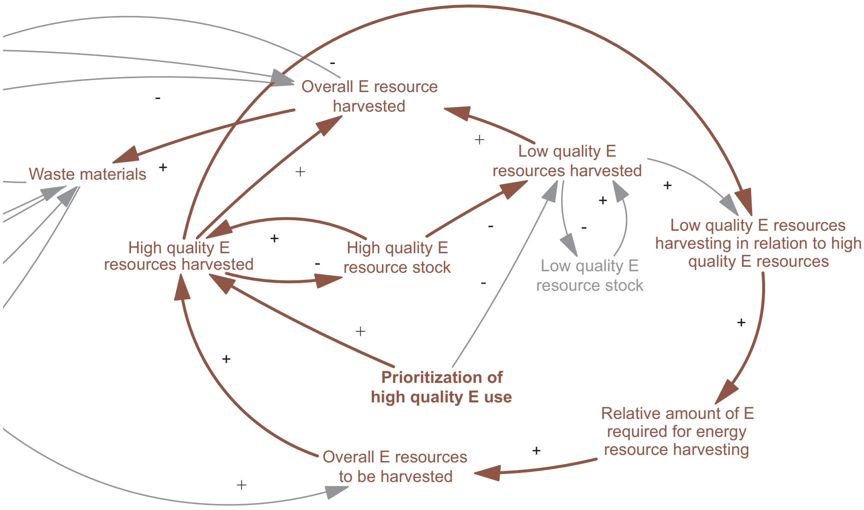

Fig. 7. Shifting to high quality energy leverage point.

This leverage point is in line with SDG 7 (United Nations General Assembly, 2015), which implicitly prioritizes high-quality energy resources over low-quality ones by aiming at providing access to affordable, reliable, sustainable and modern energy for all.

4.6. Leverage 3. The goals of the system

4.6.1. Energy sufficiency

The CLD in Fig. 8 adds two variables to the original 3 sectors (i.e. energy service use, energy service creation and energy resource harvesting) of the CLD in Fig. 3: (i) a sufficient amount of energy services and (ii) a gap between sufficient and available amount of energy services. The added structure generates a so-called goal-seeking behavior of the energy system, which thus differs it from the CLD in Fig. 3.

The energy sufficiency leverage point can be seen as a balance point. In contrast to the ever-growing energy system, it considers biophysical sink and source limits (e.g. Steffen et al., 2005; Nashawi et al., 2010; Kesicki and Anandarajah, 2011; Davidsson et al., 2014), but instead of simply minimizing energy use it is based on the assumption that having enough energy services for want satisfaction is possible (e.g. Steinberger and Roberts, 2010). Thus, a sufficient level of energy services respects environmental limits (i.e. the right side in Fig. 8), but additionally has a goal of sufficient services available for want satisfaction (i.e. the left side of Fig. 8). This leads to a goal-seeking behavior portrayed in the CLD (i.e. loop B7 in Fig. 8). The steady state of energy system should increase or decrease the generation of energy services until the gap between sufficient and available quantities of energy services is closed. The disaggregation into the Global North and the Global South categories would be relevant to this portrayal (see the similar dynamics captured in Fig. 9), since this approach facilities an examination of how an initially existing discrepancy between the amount of energy services available in the Global North and Global South drives the balancing dynamics for closing the gap between sufficient and available amounts of energy services in different parts of the world. While the dynamics of closing the gap is balancing for both the Global North and the Global South, the amount of energy services for the less developed countries may need to be increased. At the same time, the amount of energy services for the more developed countries

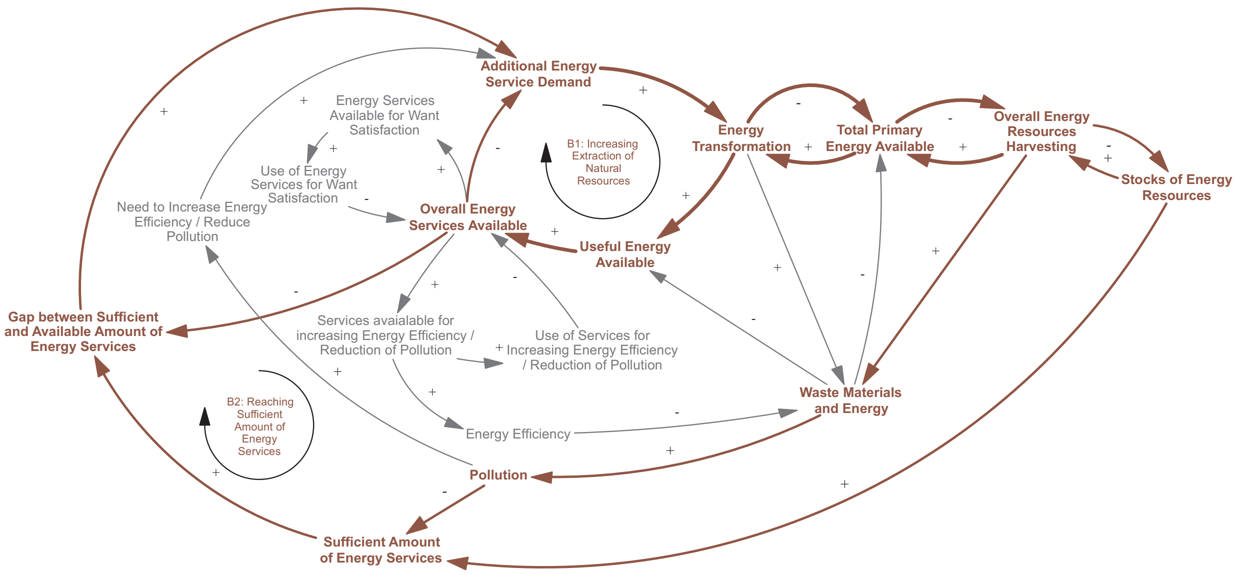

Fig. 8. Energy sufficiency leverage point.

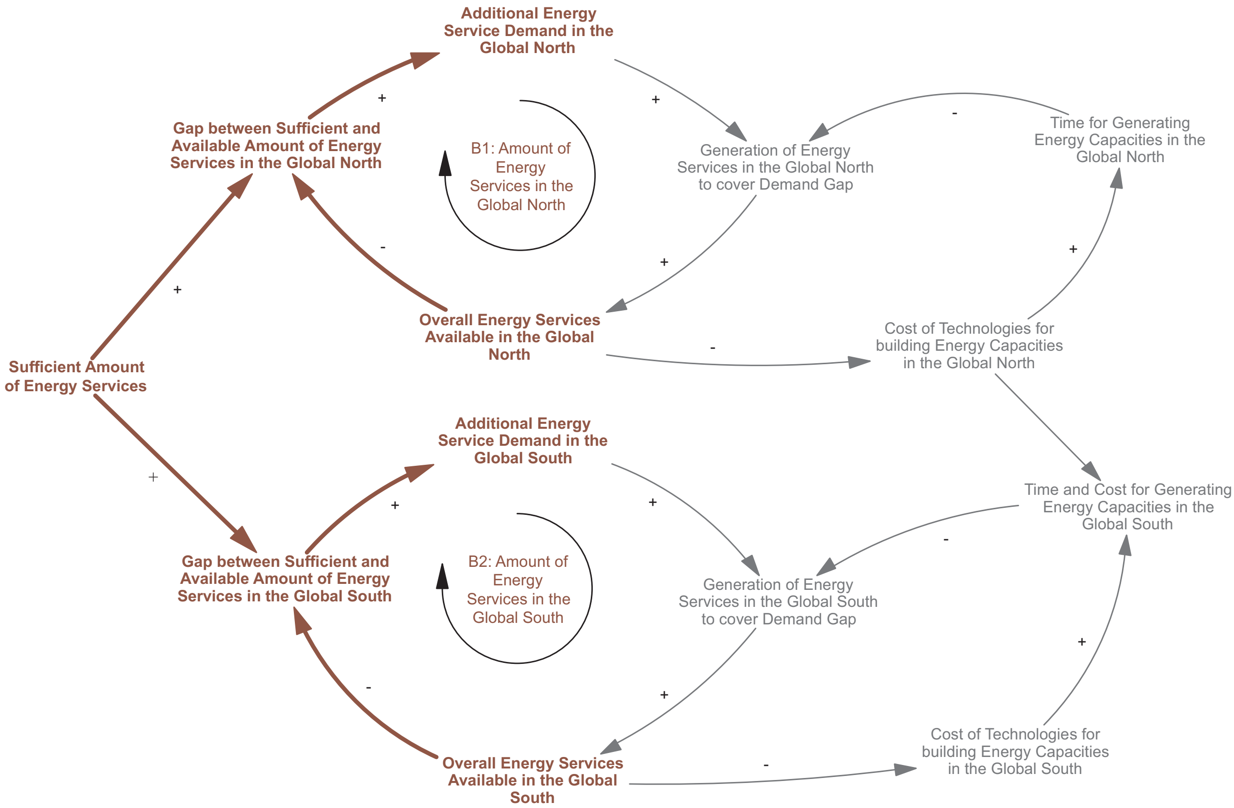

Fig. 9. Energy justice leverage point.

may need to be decreased (see Steinberger and Roberts, 2010).

Energy sufficiency is a leverage of higher influence, because it sets a clear systemic goal for energy demand.

4.7. Leverage 2. The mindset or paradigm out of which the system

4.7.1. Energy justice

The CLD in Fig. 9 combines the structure of the CLD of the technological transfer in Fig. 6 with the idea of goal-seeking behavior for reaching a sufficient amount of energy services (Fig. 8). It extends the idea of exploring dynamic interactions between the Global North and the Global South by adding 2 extra balancing loops that regulate the process of reaching a sufficient amount of energy in different regions of the world.

The idea behind an energy justice leverage point is an acknowledgement that, in some cases, especially in developing countries, there still needs to be a phase of growth in order to provide socio-economic development that allows for poverty reduction and improved livelihoods (IIASA, 2012). Therefore, when applying the leverage point analysis to the steady state of energy, it is viewed as a global concept as advocated by Kerschner (2010). He argues that the steady state could be used at a global level in which the Global North degrows in terms of service demand and the Global South grows, both converging towards a balance point.

Hence, energy justice is a global systemic goal for achieving a steady state of energy system. It is closely connected to the energy sufficiency leverage point. In fact, achieving availability of energy services for want satisfaction at a sufficient level for everyone globally can be seen as one of the key energy justice indicators, which is illustrated in the CLD above (Fig. 9). However, energy justice is more than reaching energy sufficiency. It can be seen as an ethical framework which aims at changing mindsets about the energy system. Thus, it belongs to the leverage points of a higher impact. Energy justice is about focusing on a fair distribution of energy services cost and benefits. This implies deciding on how to design an energy system in a non-discriminatory way, which would take into account economic and political differences both between and within nations. Designing energy systems in this manner should take into consideration intragenerational and intergenerational equity (Sovacool and Dworkin, 2014), and acknowledge the existence of common global sink and source limits.

Although the concept of energy justice is regarded to be of high leverage, it is only emerging recently in the energy literature (Jenkins et al., 2016; Forman, 2017; Munro et al., 2017; Sovacool et al., 2017). It has not been explicitly addressed at the policy level, but resonates with the concept of environmental justice (Walker, 2012) as well as with the contraction and convergence theory existing within the climate change debate (Meyer, 2000; Höhne et al., 2006).

4.8. Leverage 1. The power to transcend paradigms

4.8.1. Steady state, degrowth and growth of the energy system

The steady state economy claims to be a change in a mainstream growth-oriented paradigm that pushes the biophysical system, offering the solution of reaching a long run stability of environmental and socio-economic systems. Our analysis shows that there are several controversies associated with the steady state as Daly formulates it. However, the author himself addressed this aspect in his works in relation to the economy, saying that phases that require higher resource throughput should be followed by phases that require lower resource throughput in order to regain a sustainable level of resource use (Daly, 1974). The same idea applies to the steady state of energy system. Hence, energy efficiency and waste material reduction measures always need to occur during times of growth and cannot occur constantly, unless services for want satisfaction are reduced. This would mean that the energy system's goal should be seen not as a static one, but a dynamic one. Hence, when necessary, this perspective allows the paradigm at certain times and in specific locations to change from the steady state mode to the degrowing or even growing mode.

5. Conclusion

Conducting conceptual dynamic analysis of the energy system based on Daly's steady state theory lays out the obstacles and limits for designing a sustainable energy system.

This is due to the fact that displaying the steady state of energy in a systemic manner facilitates an exploration of policies aimed at sustainable energy system development as part of broader causality structures. In this way, it becomes evident that the effect of policies can go beyond their direct intentions, as they can impact multiple variables embedded in an energy system's feedback structure. Sometimes the dynamics arising from those policies can be associated with undesired side-effects, including additional pressures on the biophysical system in the long run. One of the main goals of many sustainable energy policies is increasing efficiency. An increase in efficiency may trigger a number of dynamics within the system that hinder the achievement of a sustainable energy system. This is the case despite the exclusion of the rebound effect, which is usually referred to as the main reason why policies targeting energy efficiency may fail. However, the presented analysis shows that even if external drivers, such as population growth or the rebound effect are absent, a steady state of energy and, thus, a long-term sustainable energy system, may be difficult to achieve in practice.

The leverage points concept is used in this study as an instrument identifying effective intervention mechanisms for achieving a sustainable energy system. By applying the framework of Donella Meadows, it becomes possible to rank them according to their level of impact. Hence, it is related to policy making as it supports the identification of intervention points. Additionally, it enables feedback analysis as it allows for an examination of how certain policies affect the existing energy system structure.

Several leverage points of lower and higher impact were discussed in this study. Energy efficiency, shifting to renewable energy sources, pollution and waste material reduction are classified as the leverage points of lower impact. Technological transfer, shifting to high quality energy resources, energy sufficiency and energy justice are considered to be leverage points of a higher impact. A comparison between current energy policy examples with the identified leverage points revealed that most energy policies correspond to lower impact leverages. According to Donella Meadows, leverages of higher impact are also of higher complexity. Therefore, addressing them requires policies that are more difficult to design and implement. However, the energy system can be defined as a complex system. Hence, leverages of lower impact are unlikely to lead to a sustainable energy system due to their lack of dealing with the system's complexity, such as the case associated with increasing energy efficiency.

Since the global energy system exists within the same biophysical source and sink constraints, applying the steady state theory to a global level is seen as a valid step. At this level, the theory helps to reveal the interrelationships between energy systems of different contexts around the globe (i.e. Global North and Global South energy systems), which are constrained by the same resources. By conducting a conceptual analysis of energy systems of different scales, it becomes apparent that the goals of a sustainable energy system need to be globally defined, but their translation into national or regional goals and their implementation depends on the specific context. While policies in the Global North should be much more concerned with decreasing their environmental impact (probably requiring degrowing the energy system at least to some extent rather than aiming for decoupling GDP from energy), the focus of countries in the Global South remains the provision of sufficient energy services and energy system growth.

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6. Paper V: Combining the socially sustainable energy system narrative with system dynamics modeling: A case of electricity sufficiency for Sub-Saharan Africa

Combining the socially sustainable energy system narrative with system dynamics modeling: A case of electricity sufficiency for Sub-Saharan Africa

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Key words: Sub-Saharan Africa, energy access provision, socially sustainable energy system narrative, energy sufficiency, energy justice, system dynamics

Abstract

This study presents a socially sustainable energy system narrative. It is based on two pillars: energy sufficiency as the universal energy system goal and the energy-justice-based principles of energy access provision. The constructed narrative provides an operational theoretical foundation for choosing energy provision technologies that can be considered socially sustainable and offers an alternative to a prioritizing cost-minimization mindset. Through a case of household electricity provision in Sub-Saharan Africa, the narrative is applied as a set of theoretical assumptions for energy system modelling. The presented model explores to what extent different combinations of centralized, decentralized, fossil-fuel-based and renewables-based electricity access provision are compatible with the principles of socially sustainable energy system design. Comparing three different scenarios of electricity access provision using centralized and decentralized fossil-fuel-based and renewables-based electricity generation technologies, this study concludes that decentralized and renewables-based electricity generation mixes are associated with higher cost but also with greater social sustainability benefits. By combining a conceptual narrative of socially sustainable energy systems with system dynamics modeling, theoretical work on sustainable energy system development is bridged with the energy system modelling practice. The research design of this study may interest scholars working on the theoretical development of sustainable energy system principles and their application in modeling as well as energy system modelers.

1. Introduction

Today's global energy system is in crisis. Some parts of the world suffer from a lack of energy access, leading to insufficient provision to meet human needs [1]. At the same time, other regions experience excessive energy consumption. A long list of other problems associated with the global energy system design include unaffordable energy for consumers, pollution, climate change, economic and political inequalities [2, 3].

1.1. Importance of energy system narratives and energy system goals

Dealing with energy problems is a complex task, which calls for novel methodological approaches and new ways of thinking. Today, a great amount of intellectual and political efforts are directed at solving the energy crisis and designing solutions for reaching a sustainable state of the energy system. However, these efforts often miss a fundamental component – questioning the current energy system narrative [4].

The concept of narrative is not explicitly addressed in energy system research. It is, for example, much more present in alternative-to-growth economies research field (e.g. degrowth, post-growth, sufficiency economy), where elaborated social narratives act as detailed scripts on how the economies of the future could look like [5]. Having similar types of narratives – detailed scripts of what an energy system in the future could look like – could help faster and more sustainable energy system transformations, broadening the perspectives of re-thinking and re-imagining the energy systems of the future. However, even if narrative as a term is not widely present in the energy discourse, there is still an implicit social narrative defining what an energy system is and how it should be organized.

Today, despite acknowledging the complexity of energy system crisis, it is still common to think of the energy system as a techno-economic one, organized around cost-minimization principles. Within such a narrative, sustainability transitions would be primarily techno-optimist. This is reflected in energy research, which has been dominated by research questions related to technical advancements and cost-minimization objectives [6]. However, it is crucial that today all sustainability aspects of the energy system, including biophysical, economic and social components, are explicitly included in the dominating energy system narrative. As soon as they are included, solutions for addressing the multiple dimensions of the energy system crisis would become more diverse, thereby going beyond cost-minimization thinking.

Among all the sustainability components in the currently dominating energy system narrative, the social sustainability component is the weakest one and in the current energy systems literature, the social sustainability dimension of the energy system is largely missing. As a result, there is considerable potential for the social sciences to make a contribution to the sustainable energy system research agenda [7, 8]. Calls for social science and interdisciplinary approaches in energy system research [8, 9] can help to fill the social sustainability gap in the energy system narrative. This study is one of the attempts to fill this gap. In this paper, a socially sustainable energy system (further – SSES) narrative is constructed and applied, and the process of its construction and application is discussed.

Any social narrative, including an energy system narrative, starts with defining the goals. In this case, it starts with defining energy system goals. Such goals set the general direction of energy system development that needs to be defined prior to designing any sustainable solutions. Sustainable energy principles that allow for achieving the goals of a SSES constitute the second component of the energy system narrative as it is defined in this study. Such principles are the underlying rules that that help to guide technological choices for SSES design.

Discussion on what are the energy system goals is underrepresented in the public and research discourse. Most commonly, the context in which energy system goals are discussed and are named as such, is the context of the Sustainable development Goals (SDGs). Sustainable development goal 7 (SGD7) directly states the objectives of sustainable energy system development. At the same time, despite mentioning the targets and indicators for energy system development by 2030, and being specific about aspects of a desirable energy system design (e.g. providing universal energy access, prioritizing energy efficiency, increasing use of renewable energy sources) [10], SDG7 does not give a holistic understanding of what a sustainable energy system is. Most of the sustainable energy system targets within SDG7 are, in fact, a set of parameters existing independently from any general vision of how desired energy system might look like. Therefore, SDG7 is not sufficient for formulating a SSES narrative. In contrast to SDG7, energy sufficiency, defined as a maximum desired amount of energy per capita to be produced and consumed, is discussed in this paper as the universal energy system goal. This explores how reaching the goal of energy sufficiency globally can be qualified as reaching the sustainable energy system goal.

1.2. Energy access provision

Securing universalaccess to high-quality energy, including electricity access, is among the top sustainable development priorities. This is explicitly addressed in Sustainable Development Goal 7 (SDG7) [1]. According to the IEA, access to electricity is defined as "a household having reliable and affordable access to both clean electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average" [2]. Worldwide, more than 1 billion people are living today without access to electricity (Fig.1). When it comes to the number of people lacking electricity access, the situation in the Global South [23], in particular in Sub-Saharan Africa, is the most critical (Fig.1).

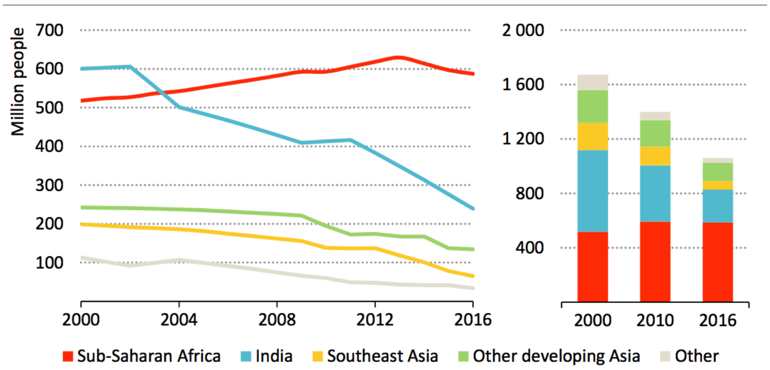


Fig. 1. Population without access to electricity by region (Source: IEA [2] World Energy Outlook-2017 Special Report: Energy Access Outlook. All rights reserved)

Active measures at the international level to provide electricity access have taken place over the last two decades [3] (Fig. 2). However, the fact that energy access provision has been implemented does not mean that energy access provision solutions have been chosen in accordance with sustainability principles. Based on Fig. 2., which depicts the energy resources used to provide electricity access in developing countries, it is evident that most electricity access since 2000 has been fulfilled using fossil fuels. Providing electricity from fossil fuels is questionable from an environmental sustainability point of view [4]. Yet some argue that the negative environmental effects associated with the use of fossil fuels can be counter-balanced by the social benefits of electricity provision [5].

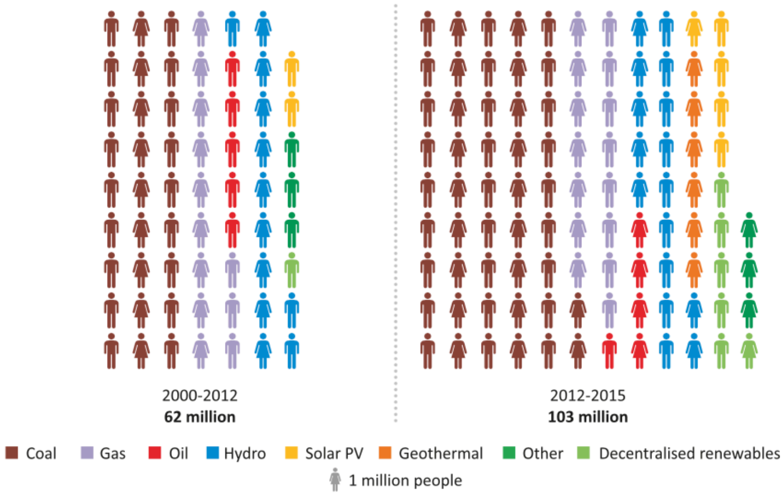


Fig. 2. Annual number of people gaining electricity access by fuel type in developing countries region (Source: IEA [2] World Energy Outlook-2017 Special Report: Energy Access Outlook. All rights reserved)

Evaluating whether in the Global South the use of environmentally unsustainable solutions could indeed be justified by its social benefits, demands the development of a normative framework, providing criteria to classify different technological solutions as either having the potential to be socially sustainable or unsustainable. SSES narrative is aimed to be an example of such a normative framework.

1.3. Methodological contribution and research questions

The main methodological objective of the paper is to bridge social science advancement in sustainable energy research [6] with the practice of energy system modelling [7], to contribute to the methods of combining quantitative and qualitative approaches when designing sustainable energy systems [8].

Theoretical part of this paper aims to contribute to the literature on social sustainability principles in energy system design by developing a framework for understanding how a SSES could be defined, and what the principles of a socially sustainable energy provision could be. Development of this framework, apart from applied, operational objectives aiming to incorporate energy justice framework into the principles of SSES design, pursues a purely theoretical objective aiming to identify connections between energy sufficiency and energy justice theory. This can contribute to theoretical development of the energy justice field, where a gap in understanding between energy justice and energy sufficiency has been identified [15, 16].

The modelling part of this paper, provides a case of how theoretical SSES narrative can be integrated into the energy system modelling practice. This approach provides an instrumental value for energy policy-making and, particularly, for designing policies for energy access provision.

Energy justice theory [13, 14] is the main conceptual instrument applied in the theoretical part of this study for formulating a socially sustainable energy narrative. It is used as the core operational framework for formulating the principles of socially sustainable energy provision. System dynamics [22] is the main method used in the modelling part of this paper.

The main research questions of this study are as follows:

(1) How SSES narrative can be defined and what are the key components of it?
(2) What are the systemic implications of incorporating SSES narratives into energy system modelling and planning?

To answer these research questions, this study presents design of SSES narrative and applies it to the case of household electricity access provision in Sub-Saharan Africa until 2040.

This study consists of 7 parts. In part two of the paper, the main components of the theoretical framework of a SSES narrative are discussed. Part three presents theoretical results of operationalizing conceptual framework for constructing the narrative. Part four provides details of how modelling is connected to the theoretical work at the different stages of the modelling process. Part five gives an overview of the model structure, including its qualitative and quantitative modelling phases. Part six presents the results of the three different simulation scenarios and discusses them in the context of socially sustainable energy policy design. In part seven, the conclusion is provided.

2. Theoretical framework

In the theoretical part of study, the energy system and energy system goals are discussed at the global scale, with the aim to understand the universal principles and underlying dynamics of energy system design as it transitions towards social sustainability. This section aims to establish a theoretical basis for determining the goals of a SSES.

2.1. Systems goal-setting. Defining energy system through the human needs lens

This study departs from the premise that energy does not have an intrinsic value and plays an instrumental role for creating opportunities for meeting human needs [17]. The energy system, correspondingly, is a socio-technical structure designed to provide energy for meeting human needs. The way an energy system is defined determines its goals and the types of socio-technical structures that need to be designed to meet them. For example, desired and feasible technological solutions for the energy system aimed at providing energy services for industrial or military purposes would be different from the solutions oriented at meeting basic human needs. At the same time, an energy system which has as its main goal the meeting of human needs would not necessarily exclude energy use beyond this purpose. However, in the latter case, energy use that exceeds the direct and indirect amount of energy needed for meeting basic human needs would be considered a secondary priority.

Theoretical assumptions behind the arguments provided in this paper are based on capability theory assumptions [18, 19, 20].

2.2. *Energy sufficiency*

Energy sufficiency is discussed in this study in the context of a SSES narrative. As a term, it means the possibility of having enough affordable energy [21]. However, there is no universal definition of energy sufficiency, as well as no universal agreement on how much energy can be considered sufficient [22].

This study focuses on the energy sufficiency concept from a social sustainability point of view and does not discuss the biophysical part of energy sufficiency in detail. The latter was explored in a previous study, in the context of the Steady State of Energy concept [27]. Based on the results of that study, energy sufficiency was defined as a universal energy system goal compatible with biophysically sustainable energy system development in the long term.

When the energy sufficiency concept is applied to the Global South, it is most commonly used in the context of a minimum amount of energy services to be provided to satisfy basic human needs [15]. The context of reaching the goals of energy sufficiency in the Global South usually implies that it is desirable to have a continuous growth of energy supply and energy consumption per capita (see e.g. the energy access definition at International Energy Agency [24]).

In the Global North context, energy sufficiency is usually associated not only with a minimum but also a maximum amount of energy to be consumed. Since it is implied that the Global North already has a sufficient amount of energy per capita, for sustainability reasons there should be a cap imposed on individual energy consumption to avoid excessive energy use [25, 26]. In this study, for both the Global North and the Global South, energy sufficiency is associated with the minimum and maximum limits of a desirable amount of energy consumption per capita.

This paper argues that energy sufficiency, with both minimum and maximum limits, is desirable from a biophysical as well as from a social sustainability perspective. Having both minimum and maximum limits for energy sufficiency is socially desirable regardless of pressures from biophysical limits. In other words, even if there are no biophysical limits in the system, the amount of energy produced and consumed should still be limited in society. This is due to certain undesirable social dynamics associated with continuous energy system growth. The arguments for the social desirability of a maximum limit for a sufficient amount of energy lack theoretical justification. An exception is the work by Illich [28]. In his work, Illich connects continuous growth in per capita energy consumption with the inevitable increase in power imbalances in society and rise of inequality. He explains the undesired dynamics of energy system growth by contrasting a high energy society with a low energy society. In the former case, infrastructure is designed in ways encouraging excessive energy consumption and preventing people from access to essential services without consuming a certain amount of energy. Long commutes from home to work or urban planning which makes it impossible to buy food without using a car are examples of high energy society infrastructure. Such infrastructure design would necessarily lead to the emergence of disadvantaged groups of people, for whom access to essential services would be unaffordable due to high energy cost. In contrast, a low energy society that includes maximum limits when considering infrastructure and broader societal design, aims to keep entry energy requirements for accessing basic social services low, thus minimizing barriers for access to social services for all social groups.

The argumentation provided by Illich was built on the societal organization and available technologies available in the 1970s, and thus can be criticized. However, despite today's increased variety of technological options for energy provision in comparison to the 1970s, energy poverty and inequality continue to be present in today´s society, and a shift to fully renewables-based energy provision cannot be seen as the solution for preventing undesired social dynamics. Therefore, Illich's arguments are still valid to explore, especially in the context of questioning the growth mindset dominating the current energy systems narrative. It is worth pointing out that this study does not argue that any increase in energy consumption and energy supply beyond a sufficiency level is undesirable. What this study argues is that having an energy sufficiency mindset as the energy system goal helps to shape a SSES narrative, leading to a more democratic and fair energy system design.

2.3. Energy justice theory

Energy justice theory is provides an elaborated up-to-date framework that aims at providing analytical and conceptual tools for designing energy systems according to social justice principles [14, 29].

A minimum amount of energy for satisfying basic human needs is connected to every human's entitlement to a minimum amount of energy. This statement is grounded in prohibitive and affirmative energy justice principles which derive from the assumption that everyone is entitled to basic goods to develop their human capacities [17]. Considering that basic goods cannot be produced without energy, everyone automatically becomes entitled to the amount of energy required for basic goods' production. This way, prohibitive and affirmative energy justice principles clarify the underlying aim of an energy system, where it has an instrumental value to help in meeting human needs, and justify why having the minimum limits of a sufficient amount of energy is essential. In this context, a sufficient amount of energy includes direct and indirect household energy consumption. The way energy sufficiency is discussed in this study emphasizes that meeting human needs is the main reason why an energy system is needed in society, where individuals and households naturally become the principal beneficiaries of the energy services.

The energy justice literature defines three pillars of energy justice: recognition, distributional and procedural justice [17, 29]. Below, each of these pillars are discussed in more detail and in connection to energy sufficiency.

Recognition justice pillar's main role is defining who must be the priority beneficiaries to receive energy services [14]. In the context of this study, the recognition justice pillar defines priority beneficiaries to be provided with a sufficient amount of energy. Meeting human needs is the main reason why an energy system is needed in society and thus individuals and households naturally become the principal beneficiaries of the energy services. Direct and indirect household energy consumption is thus a primary priority for energy system development.

Additionally, recognition justice emphasizes the importance of providing energy services to the most disadvantaged actors. Considering the lack of energy provision in the least developed world regions, individuals and households from the Global South would be at the top of the list of the sufficient energy provision beneficiaries. Consequently, from this pillar's perspective, energy access provision for the Global South should be considered a higher priority for global energy policy than energy transition is in the Global North. As for the households from the Global North (most of whom already have access to a sufficient amount of energy), as well as industrial and non-household energy consumers worldwide, they would be placed lower down in a hierarchy of energy service beneficiaries, especially those whose activity is not related to producing goods and services that help to satisfy basic human needs. It is worth mentioning that, in this study, the socially sustainable provisioning principles derived from the recognition justice pillar are based on the assumption of a regional division between the Global North and the Global South, which does not take into account local contexts and inequalities existing within developed regions of the world [34, 35]. For example, the households in the Global North that are not provided with a sufficient amount of energy will still be equally prioritized as the households in the Global South.

Distributional justice pillar is related to ensuring an equal distribution of cost and benefits in the energy system [14]. In the context of universal energy sufficiency for the Global North and the Global South, distributional energy justice would act as guidance to monitor the balances of resource and technological exchanges connected to energy access provision and energy transition policies. In particular, distributional justice would aim to prevent imbalances between the energy system cost and benefits associated with the choice of energy resources, technological solutions and financial mechanisms at local, regional and international levels.

Procedural justice pillar has to do with understanding how decisions about energy system design are made and how fair the procedures related to energy production and consumption are [14]. To ensure the highest inclusivity of decision-making, procedural justice, ideally, needs to be realized at a local scale. However, on a conceptual level, local level decision-making contradicts the idea of having a universal energy system goal, which can result only from a centralized decision-making process, provided that there is full decision-making autonomy at local levels. The idea of universal energy sufficiency implies that there is a universal normative amount of energy per capita decided upon in a top-down manner. From a distributional and recognition pillars perspective, there are no contradictions related to energy sufficiency. However, from a procedural justice perspective, defining a sufficient amount of energy is supposed to be the result of a democratic and participatory decision-making process, taking place locally. This means that individuals and communities might potentially agree on very different amounts of energy that can be considered sufficient. This would apply for both minimum and maximum levels of sufficiency. According to the procedural justice principle, everyone should be able to decide locally how much energy is sufficient within biophysical limits. In this context, energy justice theory contradicts the principle of energy sufficiency as a universal energy system goal. In fact, the contradiction between energy sufficiency and the procedural energy justice pillar originates from a misalignment between the notion of universal basic human needs and procedural justice. The idea of universal energy sufficiency derives from the premise of universal basic human needs. Therefore, solving the dilemma between universal energy sufficiency and the procedural energy justice pillar requires an elaborated discussion on the procedural aspects of decision-making related to satisfying universal basic human needs. Solving this dilemma, however, is beyond the boundaries of this study.

3. Operationalizing theory for SSES narrative

In this part, the concept of energy sufficiency and the energy justice pillars are operationalized for developing the second part of a SSES narrative – the energy provisioning principles. A hypothetical application of these principles is then used to choose between different technologies for energy access provision.

In Table 1, the three energy justice pillars (i.e. recognition, distributional, procedural) are connected to specific energy provision principles, which are derived from those pillars. These principles in turn are juxtaposed with the different types of energy provision technologies. To reach the goal of universal energy sufficiency, one needs to make sure that technological solutions associated with energy transitions are chosen and designed in line with social sustainability principles. The technologies presented in the table are on a highly aggregated level (i.e. small-scale fossil-fuels, small-scale renewables, large-scale fossil fuels, large scale renewables). They do not specify particular types of energy resources or the technology used. The main aim of connecting socially sustainable principles of energy access provision with the energy provision technologies is to reveal how the principles could be used to demonstrate the types of energy provision that are most and least compatible with SSES design. A detailed discussion on the process of deriving energy provision principles from the energy justice pillars is provided below.

Table 1.
Principles of socially sustainable energy provision based on the energy justice pillars

Energy justice pillar	Energy provision principle	Small-scale Fossil Fuels	Small-scale Renewables	Large-scale Fossil fuels	Large-scale Renewables
1.Recognition justice pillar	1.1. Technological solution allows for low energy demand and absence of high energy consumers in the system	yes	yes	no	no
	1.2. Technology allows for prosuming	no	yes	no	no
	1.3. Technology can be associated with the intermittency of energy supply	yes/no	yes	no	yes/no
	1.4. Technology can be accessible on the community level for direct provision for households	yes	yes	no	no
	1.5. Technology can be accessible in the remote rural areas with no access to centralized energy systems	yes	yes	no	no

2.Distributional justice pillar	2.1. Technology allows for minimizing dependencies between the Global North and the Global South	yes/no	yes/no	no	no
	2.2. Technology can contribute to community self-sufficiency and can create community co-benefits	yes/no	yes	no	no
	2.3. Technology depends on energy resource that is geographically widely available	no	yes	no	yes
3.Procedural justice pillar	3.1. Technology can be compatible with alternative-to-growth business models	yes	yes	no	no
	3.2. Technology allows for maximizing use of locally available resources, technologies, expertise	no	yes	no	no
	3.3. Technology is associated with a low risk of creating power imbalances in the energy system	no	yes	no	no
	3.4. There is a low risk of stranded assets associated with the technology	yes	yes	no	yes/no
	3.5. Technology allows for relatively fast installation of generating capacities	yes	yes	no	yes/no

3.1. Operationalizing recognition justice pillar

This pillar prioritizes basic-needs-oriented energy provision for individuals and households in the context of reaching the energy sufficiency goal. Energy provision principles derived from the recognition justice pillar emphasize the importance of technological solutions that would be customized to the needs and living conditions of the energy service beneficiaries.

Within this mindset, technological solutions for lower energy demand would be prioritized over those that require fulfilling higher energy demand (table 1: 1.1.). Energy provision within the energy sufficiency goal would have different implications than energy provision under growth-driven assumptions. In the latter case, it is often implied that an increase in energy access for households and decrease of energy poverty are derivative of industrial energy provision and economic growth driven by the following causal chain: energy access provision for industries – economic growth – household income increase – energy affordability for households – lack of energy poverty [31]. According to this logic, preferable criteria for choosing energy technologies would be rather large-scale energy technologies based on cost-minimization parameters, with no intermittencies in energy supply and possibilities to increase energy generation capacities in the future. In contrast, when an energy system prioritizes meeting basic human needs, small-scale technological solutions could be chosen (Table 1: 1.3; 1.4), where flexibility of demand and an increase in generation capacities occurs without intermittency being a major concern. This is because the patterns of energy supply for satisfying basic needs is less demanding in terms of requiring an uninterrupted energy supply than energy-dependent production processes [32].

Recognition of households as potential energy prosumers (not only as energy consumers but also as energy producers) is another important component of this pillar (Table 1: 1.2). Prosuming implies the possibility for a household to produce energy autonomously. The most compatible prosuming technologies are, for example, solar PV and wind energy. Once the technological infrastructure for harvesting solar and wind energy are acquired, further energy generation becomes fully accessible and affordable for a household. In contrast, fossil-fuel-based energy generation technologies (e.g. a diesel generator) are not suitable for prosuming, because energy generation in this case would require ongoing fuel purchases, limiting the prosuming autonomy of a household. Typically, in a fossil-fuel-based energy system, an actor in the energy system has to accept either a role of energy producer or energy consumer [33]. Overall, energy prosuming would encourage local, community-based energy provision and local autonomy in decision-making related to energy system design, together with generating other co-benefits on a community level [33].

Additionally, technological solutions for energy provision need to take into account the energy needs of rural households, especially those living in remote areas (Table 1: 1.5). In the context of energy access provision in the Global South, this group of energy consumers is especially vulnerable [24].

3.2. Operationalizing distributional justice pillar

Aiming to prevent imbalance between energy system cost and benefits related to the choice of energy resources, technological solutions, and financial mechanisms on local, regional and international scales, the distributional justice pillar is primarily driven by the logic of fostering local/regional self-sufficiency. To discuss energy provision principles within this pillar, the terms energy affordability and energy availability are employed. These terms are widely used in the energy policy context [10] and this study re-interprets them. Here, energy is considered to be affordable if it is locally affordable and considered to be available if it is locally available (Table 1: 2.2). Local energy availability in turn would be defined not only by the availability of the energy resources, but also by the availability of the means of energy production such as technologies, professional expertise and financial resources. The understanding of energy affordability is in line with the depiction of McCauley [36], who argues that affordability needs to account for a community's capability for acquiring the technologies and knowledge needed. Prioritizing regional self-sufficiency is also the way to avoid creating technological, monetary, resource, and institutional dependencies between the Global North and the Global South (Table 1: 2.1). It is understandable that absolute localization of energy access provision would be unrealistic, especially considering international knowledge and ecological flows embedded in technologies [37]. However, aiming to maximize local energy availability and affordability should be a priority (Table 1: 2.3).

When it comes to the choice of energy resources in the context of the distributional justice pillar, fossil fuel distribution is much more geographically concentrated than renewables. However, this is true for the physical resource part. As for the technologies, when considering know-how and the financial mechanisms related to different energy provision technologies, the difference between renewables' and fossil fuel distribution becomes more ambiguous. There is, in particular, a resource mining part related to the harvesting technologies for some of the renewables [38, 39] that is often missing from the discussion on biophysical and social complexities associated with different renewable energy sources. This can be a source of new energy system injustices within energy futures where most of the energy provision is renewables-based [36, 40]. For example, a local community might benefit from locally available and renewable geothermal energy. However, the high cost of exploration and extraction may result in the local community not being able to afford to harvest the geothermal resource for their own benefit. A large-scale development of the resource similarly may not benefit the local community if it is not equipped to receive electricity from the electric grid [41].

3.3. Operationalizing procedural justice pillar

This pillar deals with the procedures and overall principles of SSES design. The procedures associated with the procedural justice pillar are important for creating the conditions necessary for activating the recognition and distributional pillars. Avoiding creation of power imbalances in the energy system, as well as enabling community-trust-building, are the main driving forces of the procedural justice pillar.

Procedural justice should be oriented at creating conditions for producing and consuming energy in ways that do not drive winner and loser dynamics between the actors in the energy system (Table 1: 3.3). Within this pillar, the term energy access is employed. Similarly to re-interpreting energy availability and energy affordability, here, energy access is re-interpreted. In this context, energy access relates not only to the physical energy services for consumption, but also to the means of energy production, including institutional, infrastructural, monetary, and technological aspects (Table 1: 3.2). In the context of the energy sufficiency goal and in line with prioritizing community access provision, it is important to have access to diverse business models and forms of organizing energy production (Table 1: 3.1). Ideally, these forms of organization need to be inclusive, helping to prevent power imbalances and serving a higher-level purpose of democratic community transformation [42]. Questioning the assumption of energy system growth would open up opportunities for new types of business models for energy production and not-for-profit organizations [43]. Such forms of energy provision would be in contrast to existing practices. With regards to current energy provision practices, especially in the Global South, nowadays it is common for these to involve for-profit business activities that can foster green growth not only in the Global South but also in the Global North [44, 45]. Taking this into account, the social sustainability aspect of current energy provision practices, especially in the long run, is questionable.

When it comes to applying the principle of minimizing power imbalances for different types of energy resources, fossil fuels, compared to renewables, are more compatible in terms of creating winner-loser dynamics, because of resource distribution specificities, dependency on the stock and resource scarcity [46].

In terms of fostering community trust, from a procedural justice point of view, it is important to find the forms of energy provision that would encourage its cultivation. Based on social science research findings, a causal relationship exists between community trust and decentralized energy systems [47]. More insights and deeper understanding of how energy system design is connected to the democratic processes of a society can be found in the energy democracy literature [48, 49]. Decentralized energy access provision technologies are more compatible with the goals of trust-building. Centralized technologies, in contrast, by increasing "the spatial, social and political distances between actors", can undermine community trust [50: 44].

Another driving principle for designing technologies for SSES design is avoiding the creation of technological inertia and technological lock-ins [51, 52]. The winner versus loser principle can be applied not only to energy system actors, but also to technological solutions for energy provision. A SSES would aim to minimize technological inertia in its energy provision solutions. Large-scale, centralized technological systems have higher technological inertia than decentralized, small-scale energy systems [53]. Levels of technological inertia associated with energy system development in different regions can influence patterns of energy system transformation. In the Global North, where there are already established energy systems with a high level of inertia, transformation to a more sustainable energy system would be associated with occur over a relatively longer duration and at higher cost. Stranded assets associated with existing fossil-fuel-based energy systems are an example of the costs and challenges associated with such a transformation [54]. Along with the stranded assets, there are also "vested interests", whereby powerful energy system actors are interested in maintaining the status quo of the energy system [55].

In terms of designing sustainable energy provision solutions for the Global South, where existing energy systems are not as developed as the ones in the Global North and have a much lower level of technological inertia, it is important to choose those energy provision technologies that would minimize the chances of having undesired energy system lock-ins in the long run (Table 1: 3.4).

Finally, it is important to minimize the time for setting up an energy provision system. Prioritizing meeting basic human needs as soon as possible drives the choice of faster ways of realizing energy provision (Table 1: 3.5). The limits for choosing the fastest solutions, however, should not jeopardize all other aspects of sustainability in the long-term, including economic, environmental, political and social components.

It is important to mention that discussed principles of socially sustainable energy provision is the result of a generalized thought experiment rather than an exhaustive normative framework of socially sustainable principles of energy system design. These principles can be adjusted to specific contexts. A case study of energy provision in Sub-Saharan Africa presented below is an illustrative example of how the designed SSES narrative can be applied for energy system modelling and planning.

4. Connecting theory and modelling

Connecting a SSES narrative with energy system modelling includes three main stages:

- building a model structure based on core theoretical principles;
- simulating electricity access provision scenarios with different levels of compatibility with socially sustainable energy provision principles;

- contrasting and analyzing simulation results, exploring the cost and benefits associated with different types of electricity access provision.

An important aspect of this modelling exercise is that obtaining precise numerical modelling results or replicating historical behavior is not the principal goal. The role of the numbers presented is primarily to demonstrate the differences between basic and normative scenarios. Apart from discussing the actual simulation results, this study provides value by describing the modelling process, including setting the model's boundaries, conceptualization and structure-building phase, as well as the scenario simulation.

System dynamics [12] is used in this study as an energy systems modelling approach that includes both qualitative and a quantitative stages. System dynamics is usually applied as a method for understanding how complex systems are organized and can be transformed by exploring underlying feedback mechanisms in their structures [13, 14] and identifying leverage points for policy interventions [15].

There are several main reasons for choosing system dynamics as a relevant modelling approach for the purposes of this study:

(1) System dynamics is suitable for designing models on highly aggregated scales, where the main research focus is understanding general structural and behavior patterns [17].
(2) It has the tools suitable for both conceptual and quantitative analysis, which provides a good foundation for integrating theoretical concepts in the modelling exercise.
(3) The quantitative part of system dynamics modelling is relatively easy to use without advanced modelling skills, and the used software (Stella® Architect) has a user-friendly interface.

There are two main tools used in system dynamics modelling that are also utilized in this study: Causal Loop Diagrams (CLDs) (a conceptual tool) [18] and a simulation model (a quantitative tool) [13].

4.1. Different stages of connecting theory and modelling

This section discusses how the main theoretical components of a SSES narrative can be translated into modelling language. Table 2 presents a summary of how those components are addressed at various stages in the modelling process.

Table 2.
Connection between the modelling process and theoretical development

Stage of the system dynamics modeling process	*Components of a SSES narrative*	*How the theory is represented in the model*
1.Formulating the model's goals	Energy sufficiency is a universal energy system goal on a global scale	On the level of the model's structure, a goal-seeking mechanism [13] is modelled with energy sufficiency as a goal, in contrast to a goal of a continuous energy system growth.
2.Defining the model's boundaries	Energy sufficiency is a universal energy system goal for the Global South and the Global North.	Geographically, the scale of the model is not global, but regional – SSA. From a social justice point of view, meeting the goal of energy sufficiency in the Global South has the highest priority. For simplicity reasons, electricity for households direct use is the only energy service included in the model.
3.Conceptualizing the model's structure	According to the recognition justice pillar, households, including those in remote rural areas, are the highly prioritized groups of the energy services beneficiaries. From the procedural and distributional justice perspectives, decentralized and renewables-based	Electricity provision for urban and rural households in SSA is in the center of the model's structure. Non-household electricity consumption is beyond the model's boundaries. On the electricity generation side, there are four general types of electricity generation technologies: centralized fossil-fuel-based,

	energy access provision are the most compatible with socially sustainable energy provision.	centralized renewables-based, decentralized fossil-fuel-based, decentralized renewables-based. Nuclear energy is not included in the model structure for simplicity reasons, because it meets very few requirements related to the socially sustainable ways of energy access provision.
4.Formulating assumptions for the model's simulation scenarios	A list of criteria has been designed for socially sustainable energy access provision based on energy justice principles (Table 1). Different energy technologies match with those criteria to a varying extent. The technologies that are the most compatible with the socially sustainable principles of energy access provision should be prioritized.	Basic and normative scenarios are simulated in the model. In the normative scenarios, those technologies that do not qualify for socially sustainable energy access provision are excluded from the simulation.

A model-building process is about finding the balance between a model's usefulness and its complexity. It was previously mentioned that the purpose of this modelling effort was not to design the most detailed possible system of electricity access provision in SSA but to build the structure that would include the main components of a SSES narrative.

5. Model description

The model demonstrates electricity provision for rural and urban populations in SSA from 2016 until 2040. In this section, only the principle components of the model structure are discussed. The main model inputs and equations are provided in the supplementary documentation in Annex 1.

5.1. Model's goals

As was mentioned in Table 2, a goal-seeking structure lies at the core of the model, where the aim is to generate a sufficient amount of electricity for rural and urban households in SSA. Goal-seeking behavior belongs to one of the main so-called systems thinking archetypes and is considered one of the basic behavior structures in system dynamics [16, 19].

In Fig. 3, the major dynamics embedded into the model are illustrated with CLDs. From the system dynamics perspective, the driving dynamic mechanism of this model is a balancing loop, as shown in the figure. The balancing mechanism compares the sufficient amount of electricity that needs to be provided with already installed electricity generation capacity and gives the energy system a signal to increase electricity generation capacities until electricity generation reaches the level deemed to be sufficient.

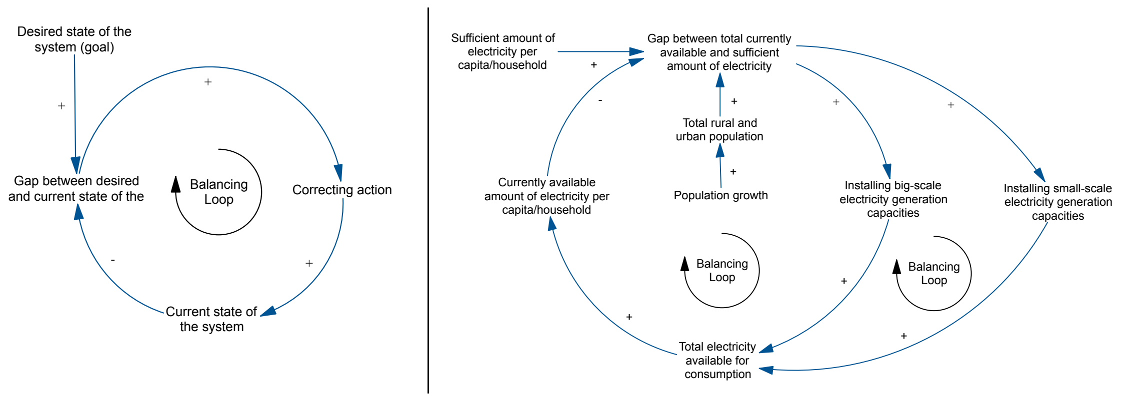


Fig. 3. CLD of a goal-seeking behavior archetype in System Dynamics in its standard representation and in the way it is presented in the model

In the model, two different goals of sufficient amounts of electricity are presented separately for urban and rural households because different amount of electricity are required when providing a sufficient amount of energy services per capita. This difference is caused by varying energy demand to support infrastructure for energy service provision [2].

It is important to mention that the goal of the model, sufficient amount of electricity per capita in SSA, does not change over time. However, the total amount of electricity to be produced and to be consumed dynamically increases due to population growth.

5.2. Model's structure: demand and supply

In Fig. 4, a CLD capturing the overall dynamics of the model is presented. The number of rural and urban households provided with a sufficient amount of electricity are the central variables in the model. The parameters of a sufficient amount of energy to be provided for rural and urban households are set at the level of 250 kWh per capita and 500 kWh per capita, respectively [2]. This amount of electricity per capita is in line with the Tiers framework of the World Bank [20], specifically, within Tier 2, which reflects the amount of electricity necessary to satisfy basic human needs.

Both centralized and decentralized electricity generation capacities are present in the model excluding the electricity grid and energy distribution systems for simplicity reasons. This limitation is reflected in the assumption that rural households should supplied only by decentralized electricity provision technologies.

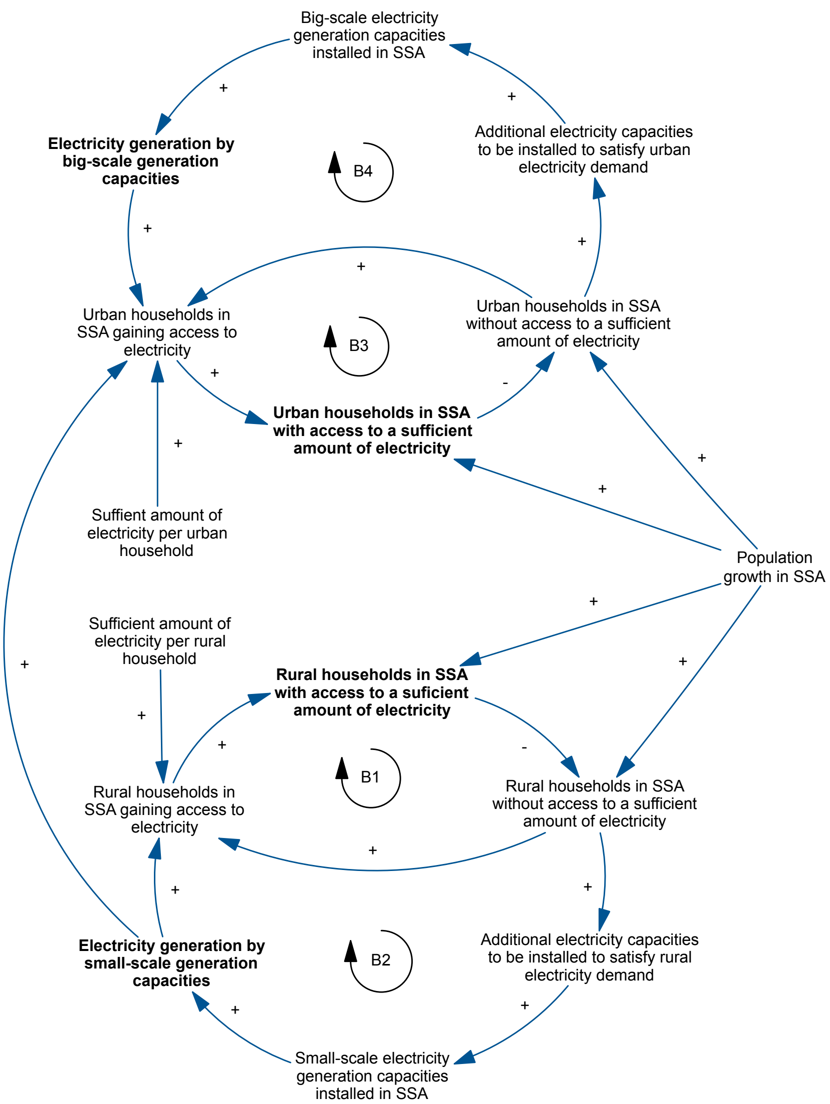


Fig. 4. Overview of the model structure in CLD

The driving dynamic mechanisms embedded in the model on the structural level include only balancing loops (see the loops labelled B1, B2, B3, B4 in Fig. 4). The four parameters in bold are key parameters in the model. Tracking their change over time facilitates answers concerning whether the goals of sufficient electricity provision for rural and urban households in SSA are reached. As a result, there are no feedback loops in the model, which would drive an endogenous increase of electricity production and electricity consumption per capita. The only parameter in the model that drives electricity generation and electricity consumption increase is population growth. GDP growth is not included in the model's structure. The reason for this is that the model is capturing energy consumption for basic human needs. Considering this, GDP is not relevant for the level of the model simplification.

The supply side of electricity access provision for SSA is presented by centralized and decentralized electricity generation capacities. Table 3 presents the list of energy provision technologies included in the model. This list is not exhaustive and includes only the technologies most commonly present in the region.

Table 3.
List of the electricity generation technologies present in the model.

Centralized electricity generation	Decentralized electricity generation
Coal	Small hydro

Gas	Stand-alone solar PV
Oil	Mini-grid solar PV
Hydro	Mini-grid wind
Centralized solar PV	Stand-alone diesel
Centralized concentrating solar	Mini-grid diesel
Centralized wind	
Centralized geothermal	
Bioenergy-based	

The mechanism of electricity cost generation is modelled in a simplified way and includes only capacity installation costs for each energy technology. For every simulation year, the model chooses a certain technological mix. This selection is based on the cost-minimization principle. However, in contrast to the models primarily driven by cost-minimization, here the lowest cost is not applied as a primary criterion for defining a technological mix. For 2016, the initial year of a simulation timeline, investment cost (in USD/kWh) for each energy technology are pre-set based on the available international energy organizations' reports (see Annex 1). After 2016, at every simulation timestep, the costs are re-calculated based on the two main driving effects: a resource-scarcity effect and a learning effect, which dynamically interact with each other and affect the cost of technologies in opposite ways. The dynamic interaction of the cost-driving CLDs is portrayed in Fig. 5.

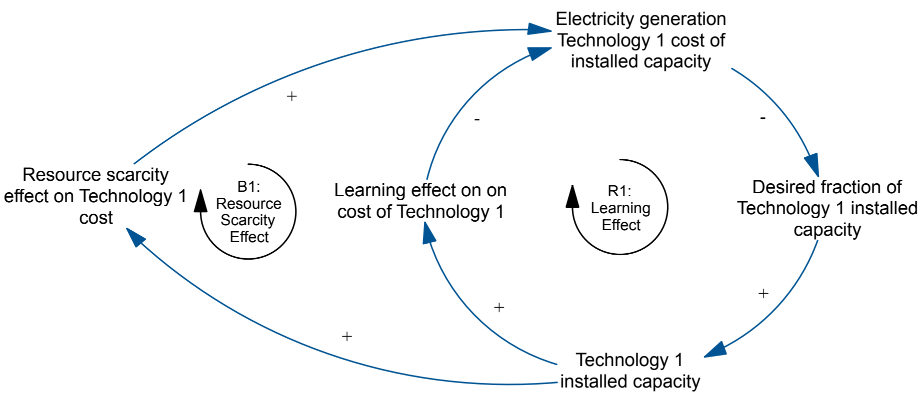


Fig. 5. CLD of the two energy cost-driving effects incorporated in the model's equations

In the model, every energy technology is modelled the same way. The amount of electricity generated by different power capacities depends on the amount of generation capacities installed as well as on their capacity factors. Explicit physical limits for the energy resources are modelled only for fossil fuels, in the form of the stocks of the corresponding resource reserves in the SSA region. Imports of fossil fuels to the region are not modelled, because the region is assumed to be self-sufficient in terms of available energy resources, which is important in terms of sustainability goals. For the renewable energies, physical limits for each energy resource are embedded in resource-cost curves (Annex 1). These curves show the effect of energy resource limits on energy cost over time. Learning ratios for each energy technology are constant, but the resulting learning effect is endogenous and changes with time, depending on total installed capacity. The system dynamics structure of the learning effect is based on Pruyt et al. [21]. Fig. 6 depicts a structure for a centralized solar PV electricity generation, which is provided as an example of how electricity generation technologies are presented in the model.

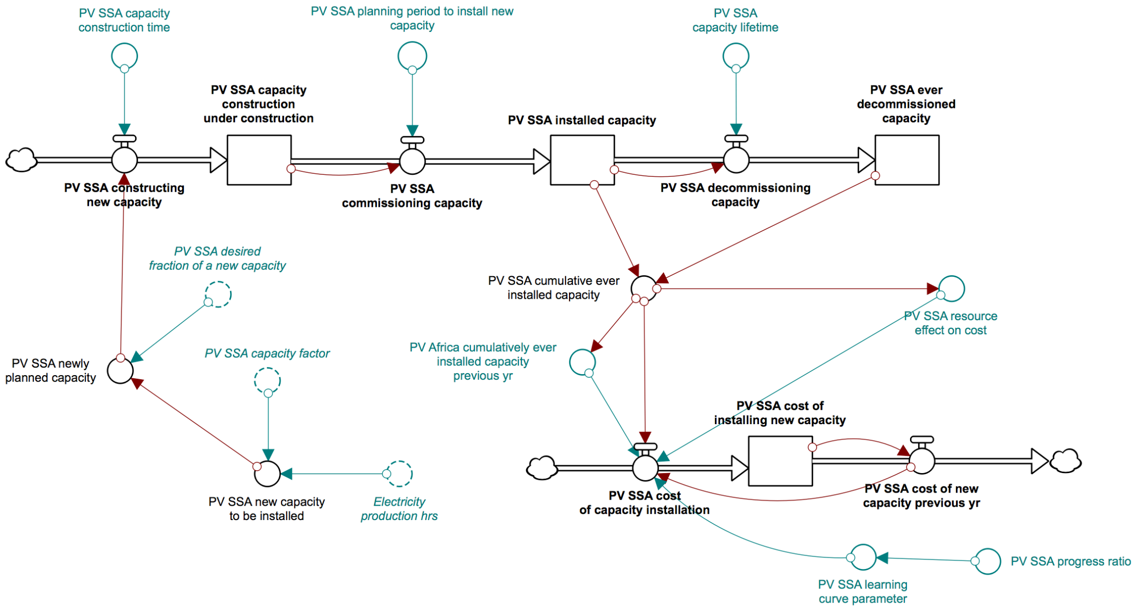


Fig. 6. Centralized solar PV power generation structure: a fragment of the model

The main structural elements of a system dynamics model are as follows: (a) stock variables, which are the square boxes presenting the values of the parameters accumulated over a certain time; (b) flow variables, which are inputs to the stock and outputs from the stocks and are portrayed as arrows with circles. Differences between inflows and outflows in each step create changes in the accumulated value of the stocks; (c) independent variables, which are circles connected to the stocks, inflows and outflows, changing their values or being changed by them.

5.3. Model's scenarios: designing rules for alternative simulation runs

At the stage of scenario simulation, three different scenarios of the model are compared. Each of them result in different technological mix of energy provision based on various allocation rules. The scenarios are as follows:

(1) Basic scenario;

In this scenario, a choice of a technological mix for electricity generation is driven by the cost-minimization principle. All the centralized and decentralized fossil-fuel-based as well as renewable energy technologies initially present in the model's structure are included.

(2) Decentralized renewables & decentralized fossil fuels scenario;

In this scenario, decentralized renewables-based and fossil-fuel-based electricity generation technologies are included, while centralized renewables-based and centralized fossil-fuel-based technologies are excluded. Cost-minimization principle is a secondary technology selection criterion in this scenario.

(3) 100% decentralized renewables scenario;

In this scenario, only decentralized renewables-based electricity generation is possible. All other technologies are excluded from the potential technological mix. Within the decentralized renewables, cost-minimization criterion is applied for defining a resulting technological mix.

The rationale behind having the normative scenarios (i.e. scenarios 2 and 3) is to design the rules for selecting electricity provision technologies based on socially sustainable energy provision principles (Table 1) in accordance with the SSES narrative. In these scenarios, technologies that are least compatible with those principles are excluded from the normative scenarios, even if they allow for the cheapest and fastest electricity provision. Based on this logic, large-scale, fossil-fuel-based technologies, as well as large-scale renewables-based technologies, are excluded from the normative scenarios. As for the decentralized technologies, renewables-based solutions are more compatible with socially sustainable energy provision than fossil-fuel-based technologies. However, according to Table 1, decentralized fossil-fuel-based technologies are also compatible with most principles of socially sustainable provision.

For all three scenarios, the overall goal of the simulation is to provide urban and rural households with a sufficient amount of electricity during the simulation period from 2016 to 2040. A comparison between the three different provision scenarios depicts differences in electricity access provision, system-wide levelized cost, and the mix of electricity generating technologies and energy resources.

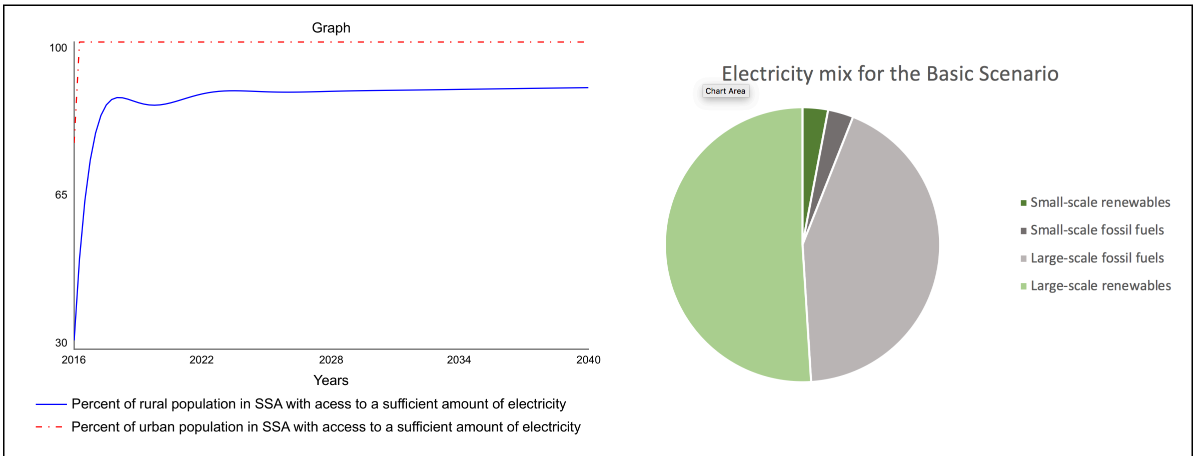
6. Results and discussion

6.1. *Modeling results*

In this section, the main results of the scenarios' simulations are presented and discussed. Three main parameters are included in the summary table with the model simulation output (see Figs. 7, 8, 9):

(i) Percentage of the rural and urban population in SSA provided with a sufficient amount of electricity measured by bln people;
(ii) Average system-wide levelized cost of electricity generation in 2016-2040 measured by USD per kWh;
(iii) Technological mixes for electricity generation measured by percentage of different technologies in the total energy mix.

Basic scenario



Percent of households provided with the sufficient amount of electricity in SSA by 2040:

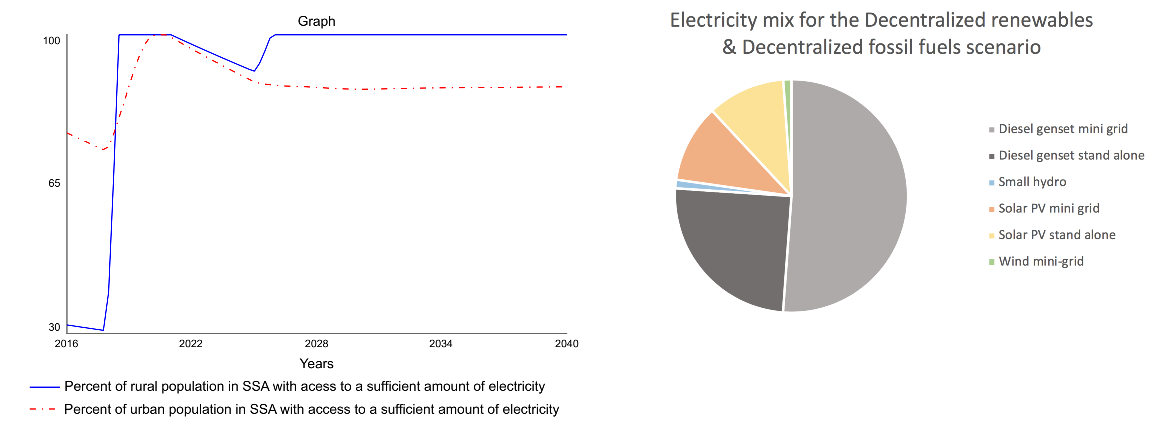
100% urban households (1bln people);

90% rural households (1,03bln people).

Average system-wide levelized cost of electricity generation in 2016-2040: **0,45 USD/kWh**

Fig. 7. Model simulation output: basic scenario

Decentralized renewables & Decentralized fossil fuels scenario



Percent of households provided with the sufficient amount of electricity in SSA by 2040:

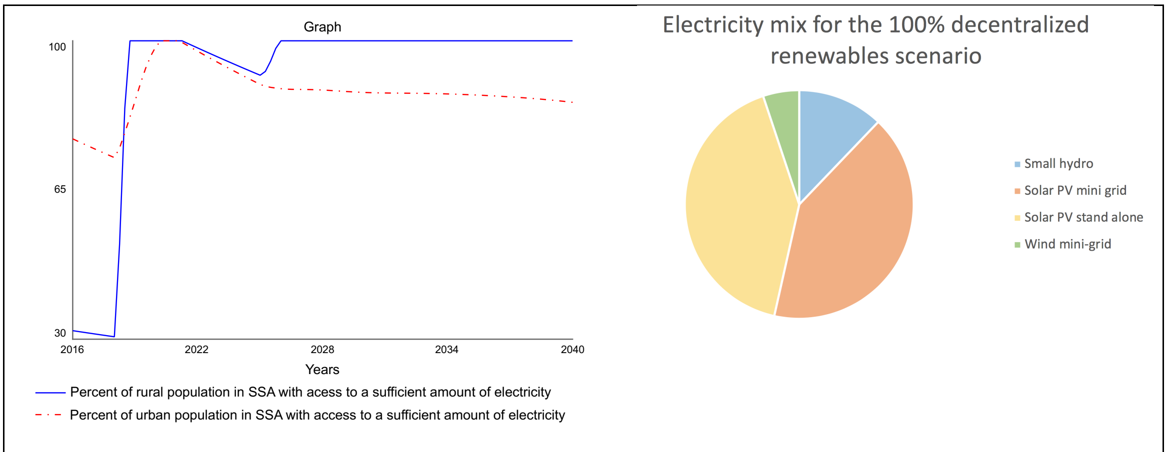
100% of rural households (1,15bln people);

88% of urban households (878mln people).

Average system-wide levelized cost of electricity generation in 2016-2040: **0,70 USD/kWh**

Fig. 8 Model simulation output: decentralized renewables & decentralized fossil fuels scenario

100% decentralized renewables scenario.



Percent of households provided with the sufficient amount of electricity in SSA by 2040:

100% of rural households (1,15bln people);

86% of urban households (855 mln people)

Average system-wide levelized cost of electricity generation in 2016-2040: 4**,11 USD/kWh**

Fig. 9. Model simulation output: 100% decentralized renewables scenario

As mentioned earlier, due to the model's limitations, the comparative results of the different scenarios are more informative and relevant for the purposes of this study than their absolute numerical outputs. In Table 4, the outputs of the three different scenarios are presented in a relative format, which allows for easier comparison of the scenario results based on the three main parameters detailed above.

6.1.1. Electricity access provision

Among all three scenarios, scenario 1 allows for the highest percentage of electricity access for urban population in SSA by 2040. Scenario 2 and 3 show a lower percentage of urban provision and higher percentage of rural provision than scenario 1. However, none of the scenarios generates 100% sufficient electricity access for both the rural and urban populations. The reason for this is the effect of population growth which effects the goals of sufficient electricity provision, making total electricity demand a moving target that changes in every simulation step. If the model structure included a population growth forecast for planning installation capacities, the gap in provision would be filled and 100% sufficient electricity access would be reached.

Table 4 illustrates that a maximum level of electricity provision is reached during the first few years of the simulated duration in all three scenarios. The reason for this is the simplified model structure which assumes immediate information exchange between demand and supply; the absence of technological, economic, social and political obstacles for increasing electricity generation capacities; and the constant availability of financial resources for investing in new generating capacities. The only type of time delays present in the model are associated with the time needed to install additional electricity generation capacities. However, the model does not comprehend the full complexity and trade-offs associated with the use of different electricity generation capacities. All of the delays and obstacles present in the existing energy systems should be taken into account when designing sustainable energy systems [3]. Regarding the modelling results, even though the exact values of the numerical simulation are not the main focus, they inspire a further discussion on what can prevent or foster speedier electricity access provision in reality.

One more interesting aspect related to this part of the results is understanding how population growth is related to the overall electricity sufficiency vision at the core of the modelling exercise. Here, the question is: can the model still be considered compatible with the energy sufficiency narrative as opposed to the energy system growth one, considering that in the model total electricity supply and demand increase over time due to population growth? It is argued that the answer to this question is the affirmative, with the model remaining compatible with the energy sufficiency narrative. Regardless of the presence of a population growth factor, a model can still be classified as one of sufficiency provided the following conditions are fulfilled: (a) the amount of sufficient energy per capita does not grow over time; (b) the way the energy system is organized prioritizes households as the main beneficiaries.

6.1.2. System-wide levelized cost

As the cost structure of electricity generation in the model is simplified (see 5.2. and Annex 1), absolute values of cost are less important than comparative ones. According to the simulation results, scenario 1 is associated with the lowest system-wide levelized cost of electricity generation. The average cost of electricity generation in scenario 2 is 55% higher than in scenario 1. Scenario 3 is most expensive one. In this scenario, system-wide levelized cost is nine times higher than in scenario 1 and six times higher than in scenario 2. Interestingly, even in scenario 1, where centralized fossil-fuel-based electricity generation is included, the share of renewables in a technological mix is larger than the share of fossil fuels. This means that even based on solely the cost-minimization principles of technological selection, fossil-fuel-based technologies are less competitive than renewables-based ones. This is an interesting finding in the context of energy access provision involving projects that have been to a large extent fossil-fuel-powered, as was mentioned in the Introduction (see Fig. 2). This simulation result, in fact, questions how reasonable and desirable fossil-fuel-based electricity provision in the Global South is, not only from a social sustainability point of view but even from a pure cost-minimization perspective. Of course, independently from cost, renewables-based energy provision would be limited by a local resource availability in the region which is present in the model only to a limited extent. Nevertheless, scenario 1 inspires a discussion on whether current technological choices of energy access provision are really driven by cost-minimization principles or are additional driving forces of a continuous investment in fossil-fuel-based electricity provision rooted in path dependency [22].

6.1.3. Mix of electricity generating technologies and energy resources

Technological mixes associated with the different scenarios of electricity access provision that are discussed and compared in this part correspond to the simulation results for 2040. They do not show how electricity generation mixes have changed dynamically over the entire simulation period.

In scenario 1, the shares of renewables and fossil fuels in 2040 are comparable, in both centralized and decentralized electricity mixes. Interestingly, in scenario 2, the share of fossil-fuel-based technologies in a decentralized technological mix is 76%, which is 30% higher than the total share of fossil fuels in the decentralized electricity generation mix of scenario 1. This result is caused by the fact that, in scenario 2, diesel electricity generation gains momentum at the beginning of the simulation and fills a large share of the gap in electricity supply. Rapid increase of diesel-based generation capacities at the early stage leads to a cost decrease in diesel generation, leading to other renewable energy technologies becoming economically uncompetitive until the end of the simulation period. In scenario 3, solar PV becomes a technological leader. In 2040, it provides 82% of total electricity generation.

In general, interpretation of the modelling results relating to the technological mixes is limited by the modelling assumptions linked to resource limits (see section 5.2.) that are only partially addressed in the model. This is a limitation to be taken into account, especially in the scenarios with large shares of biomass, hydro-power and solar PV in the electricity generation mixes. In the case of biomass and hydro-power, which are stock-based renewables, physical availability and resource limits matter. The production of solar PV is limited by non-renewable material resources [23, 24]. The exclusion of these important dynamics result in lower levelized cost in the model's simulation output. Similarly, the high learning rates of diesel-based generation capacities in the model result in lower generating cost. The net impact of these results is not significant as the timeframe of the modelling exercise is relatively short. However, if the simulation duration increased, it would be important to take these limitations into account when analyzing the model's output.

Table 4.
Comparative summary of the three scenarios' simulation results in 2040

Scenario name	% of sufficient electricity provision among rural population	% of sufficient electricity provision among urban population	System-wide levelized cost (compared to basic scenario)	Large-scale electricity generation technologies mix	Small-scale electricity generation technologies mix
(1) Basic scenario	90%	100%	n/a	**Total large-scale fossil-fuel technologies in the mix (43%), which include the shares of:** Gas (40%); Coal(35%); Oil (25%) **Total large-scale renewable energy technologies in the mix (51%), which include the shares of:** CSP (46%); Solar PV (34%); Hydro (14%); Geothermal (6%).	**Total small-scale fossil-fuel technologies in the mix (3%), which include the shares of:** Diesel genset mini-grid (67%); Diesel genset stand-alone (33%). **Total small-scale renewable energy technologies in the mix (3%), which include the shares of:** Solar PV mini-grid (47%) ; Solar PV stand-alone (47%); Small hydro (6%)
(2) Decentralized renewables & decentralized	+10% (higher than basic scenario)	-12% (lower than basic scenario)	+55% (higher than basic scenario)	n/a	**Fossil fuels (76%):** Diesel genset mini-grid (51%); Diesel genset stand-alone (25%).

fossil fuels scenario					**Renewables (24%):** Solar PV mini-grid (11%); Solar PV stand-alone (11%); Wind mini-grid (1%); Small hydro (1%)
(3) 100% decentralized renewables Scenario	+10% (higher than basic scenario)	-14% (lower than basic scenario)	+815% (higher than basic scenario)	n/a	**Renewables (100%):** Solar PV mini-grid (41%); Solar PV stand-alone (41%); Small hydro (12%) Wind mini-grid (5%)

6.2. *Combined theoretical and modeling results*

As results from this paper, SSES narrative consists of two main components: energy sufficiency as the universal energy system goal and the energy-justice-based principles of energy access provision. Derived from these principles, the guiding rules for developing a SSES can be summarized as follows:

(i) Energy provision solutions should be compatible with the idea of contributing to building a low rather than a high energy society (energy sufficiency goal).

(ii) Energy provision solutions should prioritize meeting the basic needs of individuals and households above any other types of energy use (recognition justice pillar).

(iii) Energy provision solutions should prevent creating power imbalances in the energy system at all levels (distributional and procedural justice pillars).

The model presented in this study incorporated the main components of a SSES narrative. On the level of the model's structure, this resulted in defining energy sufficiency as the energy system goal as well as rural and urban households in SSA as core beneficiaries of energy services.

Simulating three different scenarios aimed to test the theoretical principles of socially sustainable energy access provision (Table 3). Scenario 1 was not originally intended to be compatible with a SSES narrative. Its main role was to provide a baseline to compare the normative scenarios' simulation results. In contrast, scenarios 2 and 3 were initially designed to be in line with a SSES narrative. Simulation results demonstrated that scenario 2, which resulted in 76% fossil-fuel-based decentralized electricity provision in 2040, had a system-wide levelized cost of electricity that is six times lower than the 100%-renewables-based scenario 3. Judging by the number of socially sustainable energy provision principles (Table 1) presented in these two scenarios, scenario 3 could be considered to be more socially sustainable than scenario 2, if a multicriteria sustainability assessment was applied instead of pure cost-minimization. From a cost-benefit perspective, the benefits of cheaper electricity access provision in scenario 2 are counter-balanced by a higher social sustainability cost. Similarly, the higher social sustainability benefits of scenario 3 are counter-balanced by the higher monetary cost for electricity provision. Regarding the specific social sustainability criteria differences between scenarios 2 and 3, the criteria that are not met by scenario 2 are related to fossil fuel use, including restricted access to electricity prosuming as well as potential dependencies on fossil resources that are not locally available. Even though the aggregation scale of this exercise does not facilitate a detailed discussion of social costs and trade-offs, its intention is to provide an example of how different types of technological mixes for electricity access provision can be compared and the trade-offs between economic and social costs and benefits can be considered. Overall, this modelling exercise shows that, when monetary cost-minimization logic is applied, then renewables-based energy provision solutions are likely to be underrepresented in the energy mix. This logic, however, may lead to higher environmental and social cost and hinder universal sustainable energy provision.

The biophysical aspect of sustainable energy access provision is included in this study only indirectly in relation to resource-cost curves. However, even with the limited presence of biophysical parameters within the scenario comparison criteria, fossil-fuel-based provision is less equipped to meet social sustainability criteria and thus less compatible with a SSES narrative.

Combining a SSES narrative with the modelling exercise provided an example of a model that could grasp the key components of socially sustainable energy access provision. On the one hand, this exercise provides insights into how theoretical work related to SSES can become more instrumental for energy policy analysis and development. On the other hand, it can further energy system modelling practice by giving an example of how theoretical assumptions can be incorporated into a model. The principles of socially sustainable energy access provision can be applied for multiple purposes in relation to SSES design and assessment at different scales.

Application and further development of a SSES narrative as well as connecting it to the energy system modelling would be especially important for designing energy access provision policies in the Global South, where energy systems are not as well developed as those in the Global North, and where it is crucial to provide energy access solutions that would not lead to any undesired dynamics in the energy system similar to those in the Global North or lead to new potential energy system injustices.

6.3. Limitations and further research

One of the biggest limitations concerning the applied value of a SSES narrative designed is this study is the fact that it is disconnected from a broader economic context. In further research, the results of this study could be connected to existing alternative-to-growth economic narratives and models, especially considering that energy systems there are rarely described in more detail than being renewables-based and decentralized [58]. Additionally, very few of those narratives go beyond the Global North scale, explicitly or implicitly, tending to assume that alternative-to-growth narratives are not applicable in the Global South. Therefore, the energy sufficiency concept, as a universal energy system goal and the universal principles of energy provision rooted in energy justice, can bring new perspectives and insights into sufficient economies' narratives and models [5, 57], helping to inspire new research on understanding what economic sufficiency in the Global North could mean for the Global South and vice versa.

Further research is also needed on connecting energy justice theory with the concept of energy sufficiency as it is defined in this study. This can lead to new research questions in the energy justice field, particularly related to understanding the role of universal energy sufficiency in achieving social and environmental justice, globally and locally.

In relation to the modelling part of this study, the representation of the various costs and benefits of different energy provision scenarios can be enhanced by including the environmental cost associated with different energy provision technologies. The parameters that could be included in such analysis would likely include the environmental cost associated with building new energy generation capacities and decommissioning old capacities, and this could be estimated with respect to each and every stage of energy production and consumption [4]. Additionally, electricity grid and energy distribution systems are not included in the presented model structure. Inclusion of the grid and distribution system in the further modelling exercises and applying to them socially sustainable provision principles can give more detailed understanding of associated social, environmental and economics sustainability cost and benefits.

1. Conclusion

This study departed from the idea that the existing sustainable energy system narrative is missing a social sustainability component. Aiming to fill this gap, this research demonstrated an example of how to construct a socially sustainable energy system (SSES) narrative and how to use it in energy system modelling and analysis. SSES is defined through a combination of universal energy sufficiency and energy-justice-based principles for energy access provision.

Applying constructed SSES for modelling electricity sufficiency for Sub-Saharan Africa revealed the systemic implications of incorporating social sustainability principles into energy system modelling and planning. In particular, SSES narrative, by prioritizing social sustainability principles over cost-minimization one, can lead to selecting technological mixes for energy access provision that are associated with higher monetary cost but at the same time higher social sustainability benefits. Therefore, when cost-minimization principle is prioritized in energy access provision projects, there is a high chance for the most socially sustainable technologies to be dismissed. A further analysis of the trade-offs between economic and social sustainability of energy provision projects is especially relevant in the developing countries' context.

A methodology outlined in this study can be instrumental for energy policy design and assessment as well as energy system research. One of the possible uses of the developed framework is applying it in multi-criteria decision analysis (MCDA) in the context of energy development, in addition to economic and environmental principles.

This study can be useful for energy system modelers, especially for those interested in the integration of specific theoretical assumptions in energy model structures. For researchers working on theory development for sustainable energy system design, this study can also be relevant, providing an example of how energy system narratives can be constructed and how certain conceptual principles can be tested with the help of qualitative and quantitative modelling tools.

Annex A. Model input

(i) Initial cost of capacity installation:

Name of technology	Cost (USD/GW)	References
Bioenergy	1250*10^6	Source: IRENA [25]
Coal	3873*10^6	Source: McKinsey [26]
Concentrated solar power	7500*10^6	Source: IRENA [27]
Diesel genset stand alone	938*10^6	Source: Worldbank [28]
Diesel genset mini-grid	721*10^6	Source: [28]
Gas	1546*10^6	Source: McKinsey [26]
Geothermal	4000*10^6	Source: IRENA [25]
Centralized hydro	2800*10^6	Source: IRENA [25]
Mini hydro	5000*10^6	Source: Worldbank [28]
Oil	1546*10^6	Source: McKinsey [26]
Solar PV centralized	2500*10^6	Source: IRENA [25]
Solar PV mini grid	4300*10^6	Source: Worldbank [28]
Decentralized Hydro	5000*10^6	Source: Worldbank [28]
Wind centralized	2000*10^6	Source: IRENA [25]
Wind decentralized	2500*10^6	Source: Worldbank [28]

(ii) Lifetime of electricity generation technologies:

Name of technology	Technology lifetime in years	References
Diesel genset mini grid	15	Source: Worldbank [28]
Diesel genset stand alone	10	
Gas	30	
Geothermal	30	
Hydro	30	
Oil	30	
Solar PV centralized	25	
Solar PV mini grid	20	
Solar PV stand alone	15	
Wind power	25	

(iii) Power generation capacity factors:

Name of technology	Capacity factor	References
Bioenergy	0,8	Source: IRENA [25]
Coal	0,73	Source: EIA [29]
Concentrated solar	0,3	Source: EIA [29]
Gas	0,44	Source: EIA [29]
Diesel genset mini grid	0,44	Source: EIA [29]
Geothermal	0,8	Source: IRENA [25]
Hydro	0,49	Source: EIA [29]
Oil	0,54	Source: EIA [29]
Solar PV centralized	0,2	Source: IRENA [25]
Solar PV mini grid	0,2	Source: IRENA [25]
Solar PV stand alone	0,2	Source: IRENA [25]
Wind power	0,28	Source: EIA [29]

(iv) Population data:

Urban population without access to electricity in Sub Saharan Africa in 2016	122 mln people	IEA [2]
Rural population without access to electricity in Sub Saharan Africa in 2016	466 mln people	
Urban population with access to electricity in Sub Saharan Africa in 2016	409 mln people	
Rural population with access to electricity in Sub Saharan Africa in 2016	220 mln people	
Population growth coefficient in Sub Saharan Africa	UN forecast of population growth rate in Africa from 2,6% in 2016 to 1,8% in 2050Source:	Source: [30]
Sufficient amount of electricity in rural Sub Saharan Africa	250 KWh/people/year (based on Multi-tier framework)	Source: Worldbank [31]
Sufficient amount of electricity in urban Sub Saharan Africa	500 KWh/people/year (based on Multi-tier framework)	Source: Worldbank [31]

(v) Cost of technologies:

- Technological cost-resource curves are based on the xls approximation of the GCAM model learning curves. Source: GCAM v5.2 model documentation [32]
- *Technology X learning curve parameter = -LN(Technology X Progress Ratio)* **:** *LN(2)*
- *Cost of installing Technology X capacity= (Technology X cost of new capacity previous year)* ***** *(Technology X cumulatively ever installed capacity* **:** *Technology X cumulatively ever installed capacity previous year)* **^** *(Technology X learning curve parameter)* ***** *Technology X cost-resource coefficient.*

(vi) Technologies generation progress ratio:

Bioenergy power progress ratio	0,93	Source: [33]
Coal power progress ratio	0,99	
Concentrated solar power progress ratio	0,77	
Gas power progress ratio	0,86	
Geothermal power progress ratio	0,93	
Hydropower progress ratio	0,986	
Oil power progress ratio	0,86	
Solar PV progress ratio	0,77	
Windpower progress ratio	0,88	

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7. Paper VI: Policy Dialogue on a Bioeconomy for Sustainable Development in Thailand

SEI Stockholm Environment Institute

Policy dialogue on a bioeconomy for sustainable development in Thailand

SEI report
January 2020

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Across our eight centres in Europe, Asia, Africa and the Americas, we engage with policy processes, development action and business practice throughout the world.

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Contents

1. Introduction

This document reports the results from the second workshop, on Thailand, of the project "Policy Dialogues on a Bioeconomy for Sustainable Development", held in Bangkok, Thailand, on 28 March 2019. A report on the first pilot workshop, on the Baltic Sea region, held in Tallinn, Estonia, is available on the SEI website.

This project is part of the SEI Initiative on Governing Bioeconomy Pathways. The overall goal of the project is to facilitate a more constructive dialogue on the development of the bioeconomy in particular national and regional contexts to get a better understanding of how a sustainable bioeconomy is envisaged and the possible ways of achieving bioeconomy-related goals.

The SEI Initiative on Governing Bioeconomy Pathways uses the definition of a bioeconomy agreed at the most recent Global Bioeconomy Summit (GBS): "The production, utilization and conservation of biological resources, including related knowledge, science, technology and innovation, to provide information, products, processes and services across all economic sectors aiming towards a sustainable economy" (Global Bioeconomy Summit, 2018).

Section 2 provides some brief background on the bioeconomy in Thailand and the Association of Southeast Asian nations (ASEAN) region. Section 3 summarises the workshop methodology and section 4 summarizes the group discussions at the workshop. Section 5 reflects on the methodology used and the changes to be incorporated into the planning of future policy dialogues/workshops.

2. Background to the bioeconomy in Thailand

Thailand has set formal bioeconomy-related development goals at the national level. The main national policy document on the topic is the biotechnology policy framework.1

There are several reasons why Thailand is considered to be a country with great potential for bioeconomy-related development:

1. The high level of infrastructure development, which gives Thailand more options for high-added-value development linked to the knowledge-based bioeconomy compared to its neighbours in the ASEAN region.
2. The history of bioeconomy-related policymaking and implementation at the national level. The first National Biotechnology Policy Framework was implemented in 2004–2009, and it helped to establish the country's capacity to pursue biotechnology.
3. The Thai economy has excellent sources of raw materials with great potential for bioeconomy-related development, especially in key agricultural sectors (e.g. rice, cassava and sugarcane) (Lakapunrat & Thapa, 2017).

3. Bioeconomy policy dialogue in Bangkok: Method and process overview

The sustainable bioeconomy policy dialogue in Bangkok had three main stages: (a) conducting a participatory dialogue at the venue; (b) processing the workshop results; and (c) comparing the visions of a bioeconomy developed during the workshop with the existing visions in the literature. The methodological and process-related details related to each stage are discussed in this section.

1 Government of Thailand, Ministry of Science and Technology. *Thailand's National Biotechnology Framework, 2012–2021.* Bangkok, <http://www.biotec.or.th/en/images/document/1.pdf>.

3.1 Stage 1: Participatory workshop with the stakeholders

The workshop participants were selected on the basis of some diversity in backgrounds and expertise in the sectors associated with the development of a bioeconomy in Thailand and the ASEAN region. They were divided into three groups and asked to design sustainable bioeconomy pathways for Thailand up to 2050. Group membership was based on the background of the participants along with some division across the relevant sectors. The majority of the participants in Group 1 had a background in agriculture, which is naturally a key foundation for the bioeconomy in Thailand. Group 2 was designed for participants with experience of working on the social aspects of the development of a sustainable bioeconomy. Most of the participants in Group 3 had expertise in one or more biotechnologies. Dividing the participants in this way was expected to lead to some variation in the focus and scope of bioeconomy pathways developed by the end of the workshop.

The work evolved around the overarching question: *How do we shift to a sustainable bioeconomy in Thailand by 2050?* In addition, the participants were guided by supporting sub-questions to help design more elaborate bioeconomy visions and action plans. First, how is value created and realized in the bioeconomy? Second, who are the key stakeholders and decision makers? Third, what are the key feasible pathways to bioeconomic development? Finally, what instruments, regulations and policies are needed at different levels and how should governance processes be linked across these levels?

The group work and subsequent discussion lasted 3.5 hours, during which the participants designed a step-by-step action plan for achieving a sustainable bioeconomy in Thailand by 2050. The actions were designed in reverse, moving from the desired state in 2050 to the present time. The main expectation of the backward-looking methodology was that it would encourage the participants to be more open to ambitious and more imaginative conceptions of what a future bioeconomy could be like, in contrast to being focused on current conditions and the policy options available today.

There is no universal understanding of the sectoral divisions in a bioeconomy. Agriculture and forestry are usually included as the key sectors of a bioeconomy and as the primary suppliers of biomass. However, sectoral division in the bioeconomy is always highly contextual. In Thailand, for instance, there are several bioeconomy sectors and different pathways associated with them. These were identified before the workshop and given to the participants as a starting point. The sectoral pathways were: (a) a food and agriculture pathway; (b) a bio-based industry pathway; (c) a bioenergy pathway; and (d) a cross-sectoral pathway. These sectors correspond with the sectoral divisions in Thailand's biotechnology strategy.

3.2 Stage 2: Processing workshop results

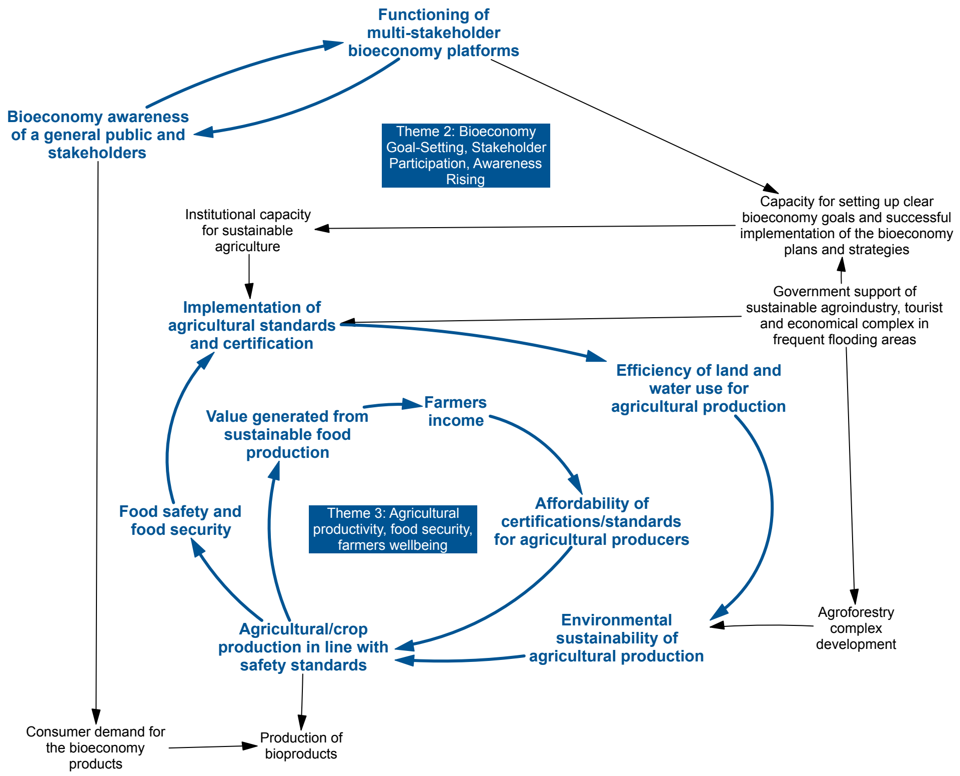
A conceptual causal loop mapping was used to analyse the workshop results, using causal loop diagrams (CLDs) as a tool (Sterman, 2000). The bioeconomy pathways were designed during the workshop as a sequence of actions connected to a timeline. In contrast, causal maps portray the actions and their interconnectedness. Of added analytical value is that the analysis reveals the underlying dynamics between the actions and provides policy insights on designing bioeconomy implementation plans in Thailand that would not be evident in the original pathways and action plans.

In the fig. 1, there are three CLDs presented. They summarize the results of the workshop and the dynamics of the key bioeconomy development themes discussed in each group.

Causal mapping of the workshop results allowed for more structured understanding of the underlying mechanisms of the selected policy actions as well as for comparing the results of the three groups. More discussion on this is available in the section 4 of this brief.

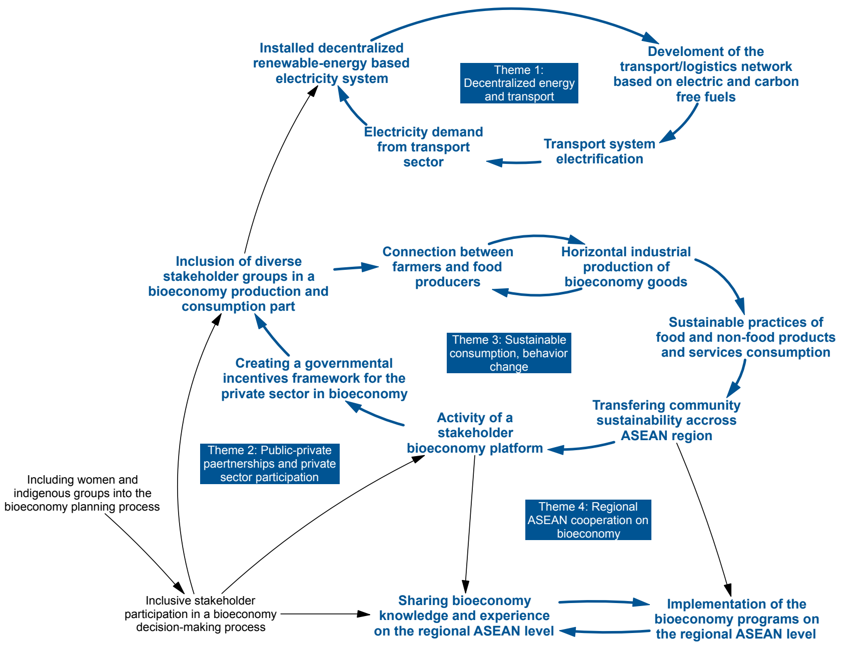
Figure 1. Causal loop diagrams

Group 1 (background in agriculture)



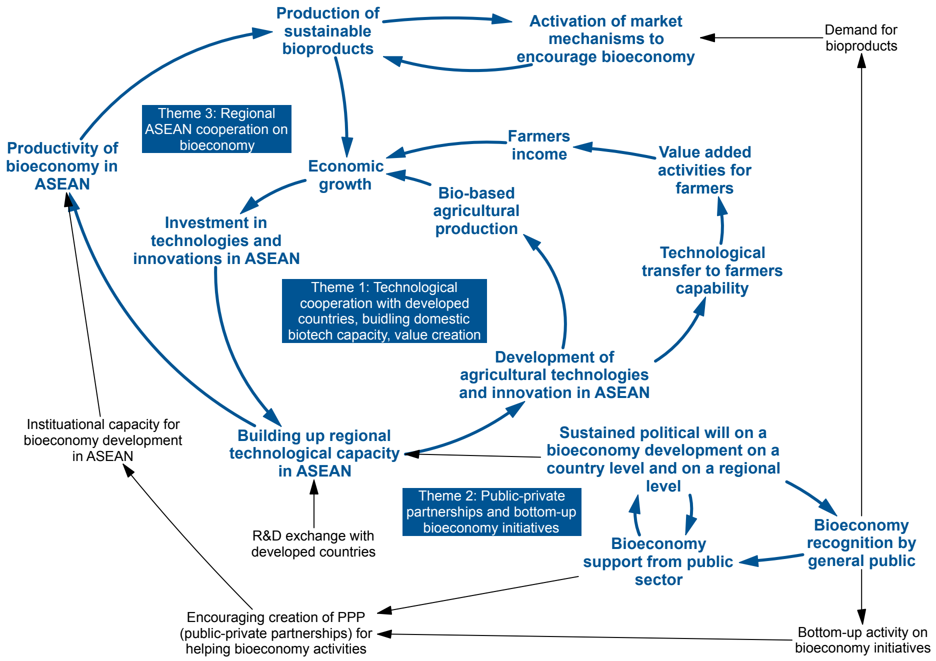
According to the Group 1, the most powerful policy feedback mechanisms are related to encouraging an increase in agricultural productivity and farmers income, as well as encouraging stakeholder participation in the bioeconomy.

Group 2 (background in working on the social aspects of sustainable bioeconomy development)



According to the Group 2, the most powerful policy feedback mechanisms are related to establishing decentralized energy and transport, connecting producers and consumers of bio-based products as well as stakeholder cooperation on the national and regional levels.

Group 3 (background in biotechnologies)



According to the Group 3, the most powerful policy feedback mechanisms are related to establishing domestic, regional and international technological cooperation as well as activation of market mechanisms for bioeconomy development and economic growth.

3.3 Stage 3: Comparing workshop results with bioeconomy visions in the literature

Three main sustainable bioeconomy visions were designed by the groups of participants as a result of the workshop. Summaries of these visions are provided in section 4. One of the goals of the bioeconomy policy dialogues is to compare the sustainable bioeconomy visions designed by the participants with existing bioeconomy visions available in the literature.

For this purpose, the sustainable bioeconomy visions designed by each group were compared with three 'reference' bioeconomy visions as synthesised by Bugge et al. (2016):

1. A *biotechnology vision* oriented towards biotechnological development and biotechnology commercialization.

2. A *bioresource vision* centred around new ways of using and creating value from biological raw materials in different economic sectors.

3. A *bioecology vision* that prioritizes environmental sustainability and the importance of ecological processes in economic and technological development.

The rationale behind this aspect of the workshop results processing was an attempt to conceptually relate the visions of a sustainable bioeconomy designed by the workshop participants to already existing, formalized visions. This process aimed to better understand the priorities and gaps in the national and regional bioeconomy visions, while also connecting the workshop results to the bioeconomy visions in the literature to create a more methodologically sound basis for comparing the results of the sustainable bioeconomy policy dialogues in different countries.

4. Workshop discussions summary: Bioeconomy pathways in Thailand

4.1 Key policy leverage points for sustainable bioeconomy pathways in Thailand

Participants in the workshop designed sustainable bioeconomy pathways and associated them with particular action points. The causal map analysis of the pathways and the action plans developed by each group revealed a number of important themes, as well as some key policy actions associated with them. Table 1 summarizes these themes and policy actions.

Table 1 shows that the choice of priority themes and actions for a sustainable bioeconomy correlated with the backgrounds of the participants in each group. However, some of the themes are present in and were prioritized by different groups regardless of the participants' backgrounds. The most notable of these are public-private partnerships and bottom-up bioeconomy-related initiatives, an increase in farmers' well-being and an increase in sustainable consumption.

Table 1. Themes and policy actions associated with sustainable bioeconomy development in Thailand

(NOTE: cells are empty where the group did not place emphasis on that aspect)

	Group 1 (background in agriculture)	Group 2 (background in working on the social aspects of sustainable bioeconomy development)	Group 3 (background in biotechnologies)
Technology and Infrastructure	**1: Energy and transport**	**1: Decentralized energy and transport** • Install a decentralized renewable energy-based electricity system.	**1: Technological cooperation with developed countries, building domestic biotech capacity** • Build up regional technological capacity in Southeast Asia. • Production of sustainable bioproducts. • Activation of market mechanisms to encourage the bioeconomy.
Stakeholder engagement and relations	**2: Bioeconomy goal-setting, stakeholder participation and awareness raising** • Functioning multi-stakeholder platform(s) for the bioeconomy. • Bioeconomy awareness raising among general public and stakeholders. • Set clear bioeconomy objectives and goals. • Increase capacity for successful implementation of bioeconomy-related plans and strategies.	**2: Public-private partnership (PPP) initiatives and private sector participation** • Activate a stakeholders' bioeconomy platform. • Inclusive stakeholder participation in bioeconomy decision-making processes.	**2: PPP and bottom-up bioeconomy initiatives** • Bioeconomy support from the public sector. • Bottom-up activity related to bioeconomy initiatives. • Encourage PPP creation to assist bioeconomy activities. • Establish a communication platform for the production and consumption aspects of the bioeconomy.
Environmental and social sustainability	**3: Crop/agricultural productivity, food security and farmers' well-being** • Agricultural/crop production in line with safety standards. • Enhance efficiency of land and water use for agricultural production.	**3: Sustainable consumption, behaviour change** • Sustainable practices of food and non-food products and services consumption, including service over ownership.	**3: Farmers' well-being**
Regional economic aspects		**4: Regional ASEAN cooperation on bioeconomy** • Sharing of bioeconomy knowledge and experience at the regional level	***4: Regional ASEAN cooperation on bioeconomy*** • Sustained political will on bioeconomy development at the country level and the regional level

4.2 Sustainable bioeconomy visions based on the workshop results

This section presents the three sustainable bioeconomy visions derived from the group work. These visions are extracted from the pathways and action plans developed by the participants.

The sustainable bioeconomy vision of Group 1

Agriculture and energy are the most substantial parts of the bioeconomy. Zero use of fossil fuels and 100% access to healthy and sustainable food are the main goals of bioeconomy development in ASEAN and are the key objectives of the development of a sustainable bioeconomy. Crop production that allows for the sustainable and efficient use of land and water, and minimum possible waste creation is a fundamental part of agriculture in a bioeconomy. A combination of mechanization and traditional crop-growing practices that take account of regional climate and weather specificities are the key knowledge-based components of the agricultural aspects of a sustainable bioeconomy in the region. Farmers will be the key beneficiaries of the value created in the agricultural sector. Farmers' incomes and poverty reduction among farmers will be the main indicators for assessing the success of a bioeconomy.

Sustainable bioeconomy development should be based on an interdisciplinary and intersectoral approach. In this way, systemic synergies can be created in the bioeconomy across sectors. A transformation of the energy and transport sectors should be based on a mix of biofuels, sources of renewable electricity and hydrogen. The shift to these sources is especially important for reaching climate mitigation goals consistent with keeping global average temperature increase below 2C. A strong participatory component and stakeholder involvement at the local, national and regional levels, combined with top-down political actions will be the core mechanisms driving clear goal-setting in the bioeconomy, as well as ensuring implementation of all the defined goals.

The sustainable bioeconomy vision of Group 2

Decentralization of energy and agricultural production is a fundamental component of bioeconomy development in Thailand and the ASEAN region. Shifting from large-scale, vertical production systems to small-scale, horizontal ones will ensure that environmental and social sustainability goals are reached. Social and technical innovations should be designed specifically to contribute to farmers' well-being. A strong participatory decision-making core is crucial for bioeconomy-related goal-setting and implementation processes. Public-private partnerships (PPP) enable the interests of the private and public sectors to be met in designing bioeconomy programmes and are one of the main instruments for realizing bioeconomy visions. The maximum diversity of stakeholder participation, enabling the inclusion of women and indigenous groups, is important and needs to be institutionalized by creating a participatory bioeconomy platform. In a regional ASEAN context, the effective coordination of the bioeconomy strategies of Asian states will be an essential component if bioeconomy visions are to be successfully realized. A shift to more sustainable consumer behaviour supported by awareness-raising campaigns will also be necessary for a bioeconomy to become fully functioning.

The sustainable bioeconomy vision of Group 3

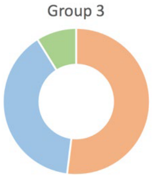
Technological development is the most essential component of bioeconomy development in Thailand. There is not currently enough technological capacity in the country and a massive boost is needed in investment in R&D. To achieve this, cooperation will be required between the ASEAN member states and between Thailand and developed countries of the global North. Top-down support for bioeconomy initiatives and sustained political will are important for fostering bioeconomy development. However, market competition among bioeconomy actors and biotechnologies should be the main driving force in activating and scaling-up the sustainable production and consumption of bio-based products. Nonetheless, coordination among different bioeconomy actors, and between producers and consumers of bio-based products, as well as overall support for bottom-up bioeconomy initiatives, will also be crucial. The creation of bioeconomy communication platforms and PPPs are valuable instruments for the constructive participation of different bioeconomy actors. Farmers' well-being and small-scale agricultural activities are important but not necessarily the core of the future bioeconomy. When major efforts are directed at technological development, farmers will also benefit. Overall, the goal of the bioeconomy is economic growth, which, however, must be environmentally sustainable and lead in particular to a decrease in GHG emissions.

4.3 Comparing the sustainable bioeconomy visions that resulted from the policy dialogue in Thailand with bioeconomy visions in the literature

Each of the three sustainable bioeconomy visions developed by the participants includes a number of environmental, technological or socio-economic priorities. The balance between the different priorities of each of the visions is shown in Figure 1. This allows a comparison of each of the visions designed during the workshop with the reference visions (Bugge, Hansen, & Klitkou, 2016) mentioned in section 3.

Based on a weighting of environmental, technological and socio-economic factors within each of the visions designed by the participants, there was no absolute match between any of them and the reference bioeconomy visions in the literature. However, it is evident that the visions of Group 1 and Group 2 are closer to the bio-ecology visions, and that of Group 3 is closer to the biotechnology vision. Interestingly, there is a strong emphasis in all the bioeconomy visions produced by the workshop participants in Bangkok on social components, especially in relation to rural development and sustainable food production. The bioeconomy vision of Group 3 is especially interesting in this context, because it includes both strong technological aspects and a strong social aspect. This is not very common since most of the biotechnological visions available in the literature largely exclude social components. The presence of a strong social component in the bioeconomy visions in Thailand, especially those related to rural development and farmers' well-being, can be explained by the cultural context and the generally high importance of rural activities to the Thai economy.

Figure 1. Comparison of the sustainable bioeconomy visions designed during the workshop in Bangkok

Group 1 	The bioeconomy vision of Group 1 prioritizes environmental sustainability, and social and well-being objectives over technological development and international cooperation. In the environmental sustainability category, the emphasis was placed on acknowledging regional climate and weather specificities (e.g. flood risks). The social components of the bioeconomy vision are mentioned by this group primarily in the context of increasing farmers' well-being and reducing their poverty.
Group 2 	Group 2 had the most balanced bioeconomy vision of the three, with an almost equal presence of all three bioeconomic categories. Group 2 and Group 3 both give technological priorities considerable weight. However, Group 2 explicitly mentions technological development in the context of decentralization goals and prioritizing the needs of local communities.
Group 3 	The bioeconomy vision of Group 3 is primarily technologically oriented and has relatively few environmental sustainability components. In contrast to Group 2, it is technological progress that drives economic growth and fosters international technological cooperation in the view of Group 3. Together with the technological priorities, a wide range of social/economic components are present in the vision of Group 3. These components are mostly related to an increase in well-being in rural areas and are primarily driven by technological progress.

Colour legend:
- Environmental Sustainability and Resource Efficiency priorities
- Technological and Cooperation priorities
- Social/Economic priorities

5. Reflections on and discussion of the stakeholder engagement methodology

Following the pilot sustainable bioeconomy policy dialogue in this series in Tallinn, various methodological aspects were changed. In particular, the principles behind the division of the participants into groups were based on their thematic backgrounds and expertise (i.e. agriculture, biotechnologies, social aspects of sustainable bioeconomy development), in contrast to Tallinn where the participants were divided into groups representing government, academia, and NGOs and the private sector. This modification allowed elaboration of more detailed and contrasting bioeconomy visions and pathways among the different groups of participants.

Causal loop analysis and a comparative analysis of the bioeconomy visions designed by the participants with the bioeconomy visions in the literature were added as stages of processing the workshop results. These additional stages contributed to a better analysis of the workshop results and will be used in future policy dialogue workshops.

The main driving question and the sub-questions provided during the workshop in Bangkok were more specific than those used in Tallinn. These questions added to the more constructive input from the participants in designing the sustainable bioeconomy pathways. One of the insights from this part of the process was that thinking within the national scale is more intuitive and less confusing for participants than thinking on a regional one. It is therefore important that the main driving question specifically notes the focus on the national level.

The main methodological weakness during the workshop in Bangkok was the lack of clarity around defining sustainable bioeconomy-related goals. Participants were encouraged to design bioeconomy pathways without first having a detailed group discussion on setting sustainable bioeconomy-related goals. This methodological shortcoming will be addressed in future policy dialogues. A part of the workshop process will be explicitly dedicated to a discussion of sustainable bioeconomy-related goals.

An examination of the connection between sustainable bioeconomy-related goals and the United Nations Sustainable Development Goals (SDGs) is an additional aspect that could contribute to enhancing the quality of the workshop results. The SDGs were mentioned multiple times during the workshop in Bangkok in terms of the broad development context. Future policy dialogues will explicitly address the interactions between bioeconomy-related goals and the SDGs in the workshop process. This will be especially relevant in the context of the less developed countries, where an exploration of the synergies and trade-offs between the SDGs and sustainable bioeconomy-related goals is particularly important.

Several more sustainable bioeconomy policy dialogues will be conducted. The final report will compare and synthesise the results of the various dialogues and draw policy-relevant conclusions based on them all.

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8. Summary and Discussion

8.1. PhD Thesis Summary

This PhD thesis explores what can be considered a sustainable energy system on a global scale and what methods and tools can help sustainable energy policy design and assessment. Structurally, there are two main areas of interest in this thesis: energy system modelling and sustainable energy system narratives. At the initial stage of the research, several research gaps were identified that became a foundation of the further research design. Those gaps were: (1) Most of existing energy system models have unrealistic or oversimplified assumptions that can negatively impact the quality of the models' outputs and consequently the quality of decision-making informed by such models; (2) There is a limited instrumental value of the available theories related to a sustainable energy system development; (3) There is a lack of global energy system narratives that would have a holistic understanding of the long-term energy system purposes (goals) and the principles of the energy system sustainable design. Based on the identified gaps, the research strategy was designed which aimed at addressing these gaps in order to answer the main research questions. As a result, there are seven papers written, most of which are collaborative studies. Below, is a brief presentation and discussion of the main research results obtained during this PhD.

8.2. Discussion of Results

8.2.1. Formulation of the current energy paradigm

The current energy paradigm was formulated in Paper I. It can be used as a guidance for a sustainable energy system modelling and as a supporting tool for analyzing and comparing assumptions of different energy system models. The current energy paradigm is driven by a sustainability agenda and includes 11 main questions that should be addressed in the energy system models in order to make their results policy-relevant:

1. How does the energy system affect climate change?
2. What other negative environmental impacts of the energy system exist?
3. How does climate change affect the energy system?
4. What are the limits of fossil resource supplies and what are their implications?
5. What are the limits of renewable resources and what are their implications?
6. How can a secure energy system be provided?
7. How does the energy system affect socio-economic development beyond GDP?
8. How will near future energy system developments shape the long-term future energy system and how do long-term future goals impact on short-term developments?
9. What are the synergies and trade-offs between different energy system development goals?
10. How does the development of the energy system of one country/region affect global

development?
11. How do global developments affect the development of the energy system of a country/region?

Based on the energy system models review, it was concluded that hybrid models and IAMs have the highest potential for addressing multidisciplinary energy system complexity which is important in the context of sustainability-oriented energy policies. However, most of the existing energy models have limitations. Those, particularly are related to modelling the limits of renewables as well as to addressing social dynamics driving energy system development and climate policy-making.

8.2.2. Conceptualization of the Steady State of Energy

Steady state of energy concept was designed inspired by Daly's the steady-state economy theory (see Paper IV). This concept implies that for energy system to be biophysically sustainable in a long run, there should be a universal goal of energy sufficiency for both the Global South and the Global North, independently from the current level of energy system development in different world regions. Energy sufficiency within the steady state of energy concept is defined as a universal energy system goal which resulted from leverage points analysis, during which several main energy policies were classified in accordance to their potential systemic impact. As a result, energy efficiency, shifting to renewable energy sources, pollution and waste material reduction were classified as the leverages of lower impact. At the same time, technological transfer, shifting to high quality energy resources, energy sufficiency and application of energy justice principles were classified as the leverage points of a higher impact. A comparison between current energy policies with the identified leverage points revealed that most of current energy policies correspond to lower impact leverages. Research design underlying development of the steady state of energy concept is in itself a useful result of this thesis, since it demonstrated an example of how to conceptualize sustainable energy system concepts and how to conduct sustainable energy policy assessment.

8.2.3. Designing a socially sustainable energy system narrative

Socially sustainable energy system narrative is defined in this thesis as a combination of energy sufficiency goal and the energy-justice-based principles of socially sustainable energy access provision (see Paper V).

Three overarching principles of socially sustainable energy provision are defined: (i) Energy provision solutions should prioritize basic needs of individuals and households above any other types of energy use; (ii) Energy provision solutions should be compatible with the idea of contributing to building low energy society rather than high energy society; (iii) Energy provision solutions should prevent creating power imbalances in the energy system at all levels.

A full list of socially sustainable energy provision principles contains the overarching principles in a more detailed version, where energy-justice-based principles are connected to the different types of the technological solutions for energy provision. This list is shown in Table 1.

Table 1. *Principles of socially sustainable energy provision based on the energy justice pillars (Paper V)*

Energy justice pillar	Energy provision principle	Small-scale Fossil Fuels	Small-scale Renewables	Large-scale Fossil fuels	Large- scale Renewables
1.Recognition justice pillar	1.1. Technological solution allows for low energy demand and absence of high energy consumers in the system	yes	yes	no	no
	1.2. Technology allows for prosuming	no	yes	no	no
	1.3. Technology can be associated with the intermittency of energy supply	yes/no	yes	no	yes/no
	1.4. Technology can be accessible on the community level for direct provision for households	yes	yes	no	no
	1.5. Technology can be accessible in the remote rural areas with no access to centralized energy systems	yes	yes	no	no
2.Distributional justice pillar	2.1. Technology allows for minimizing dependencies between the Global North and the Global South	yes/ no	yes/ no	no	no
	2.2. Technology can contribute to community self-sufficiency and can create community co-benefits	yes/ no	yes	no	no
	2.3. Technology depends on energy resource that is geographically widely available	no	yes	no	yes
3.Procedural justice pillar	3.1. Technology can be compatible with the alternative-to-growth business models	yes	yes	no	no
	3.2. Technology allows for maximizing use of locally available resources, technologies, expertise	no	yes	no	no
	3.3. Technology is associated with a low risk of creating power imbalances in the energy system	no	yes	no	no
	3.4. There is a low risk of stranded assets associated with the technology	yes	yes	no	yes/no
	3.5. Technology allows for relatively fast installation of generating capacities	yes	yes	no	yes/no

The developed principles of socially sustainable energy access provision provide an example of a normative guidance for sustainable energy policies design and assessment. It reveals that small-scale renewable energy provision technologies are the most compatible with the socially sustainable energy provision followed by the small-scale fossil fuels. Centralized energy provision technologies, regardless the types of energy resources used, are less compatible with socially sustainable energy provision. This result is particularly interesting in the context of discussing renewable energy transition and social injustices that can be potentially associated with it. When it comes to energy provision in the Global South, the designed principles which are based on social justice, could be the guidelines of how to avoid creating technological, financial, resource, political power imbalances between the Global North and the Global South.

8.2.4. Developing a system dynamics model integrating sustainable energy provision narrative

System dynamics simulation model of a sufficient electricity provision for rural and urban households in Sub-Saharan Africa is one of the main deliverables of this thesis (Paper VI). The structure of the model includes several different centralized and decentralized renewable and fossil fuel development solutions that comprise energy provision mix. Even though the technical assumptions behind modelling each technological solution are simplified, the model can be a useful tool for testing different relative cost and benefits of different energy provision scenarios. The model simulation results demonstrated relative trade-offs between a default cost-minimization scenario of energy access provision, a 100% decentralized renewables scenario and a mixed (both renewables and fossil fuels) decentralized provision one. In this modelling exercise, the research design and relative comparison of different scenario outputs are more valuable than the absolute numerical output and can be insightful for designing interdisciplinary methodologies for the future sustainable energy research. The results of this study can encourage critical thinking in relation to designing energy access provision policies showing that the technological solutions associated with the lowest economic cost can be unsustainable from a social sustainability point of view and can potentially lead to creation of undesired energy system dynamics and energy system lock-ins.

Research design behind the modelling exercise has a separate value in of itself by demonstrating how energy system modelling and a theoretical research on sustainable energy system development can be combined. This thesis demonstrates how the modelling process is linked to the developed theoretical energy system narrative at several main phases of the modelling process, from the conceptualizing phase to the scenario simulation one. In table 2, connections between the modelling process and socially sustainable energy system narrative is explained in detail.

Table 2. *Connection between the modelling process and a socially sustainable energy system narrative (Paper V)*

Stage of the system dynamics modeling process	*Components of the socially sustainable energy system narrative*	*How the theory is represented in the model*
1.Formulating the model's goals	Energy sufficiency is a universal energy system goal on a global scale	On the level of the model's structure, a goal-seeking mechanism (Sterman, 2000) is modelled with the energy sufficiency as a goal, in contrast to a goal of a continuous energy system growth.
2.Defining the model's boundaries	There are two sub-goals of a universal energy sufficiency goal: goal of energy access provision for the Global South and a goal of energy transition for the Global North.	Geographically, the scale of the model is not global, but regional – Sub-Saharan Africa. The model is focused on the Global South energy provision goal. From the social justice point of view, meeting the goal of energy sufficiency in the regions with the lack of energy access provision is of a higher priority than meeting the goal of energy transition where the level of energy services provided is already above sufficient level or the simplicity reasons, electricity is the only energy services included in the model.
3.Conceptualizing the model's structure	According to the recognition justice pillar, households, including those in	Electricity provision for urban and rural households in Sub-Saharan Africa is in the center

	the remote rural areas are the highly prioritized groups of the energy services beneficiaries. From the procedural and distributional justice perspectives, decentralized and renewables-based energy access provision are the most compatible with the socially sustainable energy provision.	of the model's structure. Non-household electricity consumption is beyond the model's boundaries. On the electricity generation side, there are four general types of electricity generation capacities: centralized fossil-fuel-based electricity access provision, centralized renewables-based electricity access provision, decentralized (off-grid) fossil-fuel-based electricity access provision, decentralized renewables-based electricity access provision. Nuclear energy is not included in the model structure for the simplicity reasons, because it meets very few requirements related to the socially sustainable ways of energy access provision.
4.Formulating assumptions for the model's simulation scenarios	There have been designed a list of criteria for socially sustainable ways of energy access provision based on the energy justice principles (i.e. recognition, procedural, distributional justice). Different energy technologies match with those criteria to a different extent. The technologies that are the most compatible with the socially sustainable principles of energy access provision should be prioritized in the energy access provision projects.	There are basic and normative scenarios simulated in the model. In the normative scenarios, those technologies that do not qualify for the socially sustainable energy access provision are excluded from the simulation, because they do not qualify as potential technologies to be chosen for electricity access provision.

The system dynamics model and the research design underlying its creation can be an inspiration for further interdisciplinary research in the domain of sustainable energy system development.

8.3. Contribution to knowledge

8.3.1. Practical

The results of this thesis have a high applied value. However, there are three main components which are seen especially valuable. Those are as follows:

(i) Constructing socially sustainable energy system narrative

Socially sustainable principles of energy access provision have a direct applied value for sustainable energy policy-making (Paper V). Principles of energy technology assessment designed in this thesis are universal and can be adjusted to any scale of the energy policy-making, from a local to a global one. The list of these principles can be adjusted according to the local contexts. Similarly, the groups of energy provision technologies (i.e. centralized and decentralized renewables and fossil fuel ones) can be disaggregated into specific energy provision technologies within each group depending on the availability of technologies in different regions. This can provide more detailed and customized input into a sustainable energy system planning and help better assessment of the trade-offs between economic and social cost associated with each technology. The developed tool can be used as a part of multi-criteria analysis for sustainable energy project assessment.

(ii) Connecting such narrative to energy system simulation modelling

Energy system models are widely used as the tools to inform energy policy decision-making. The limitations of the energy models as decision-support tools, especially in the part that relates to oversimplified representation of social reality are widely acknowledged (Paper I, Paper III). This thesis, by clearly describing step-by-step process of bridging energy system modelling with social sciences energy system research, has a high practical value and can serve as a guideline for sustainable energy policy design and assessment and can help strengthening social sustainability component of energy policy.

(iii) Leverage-point-based energy policy design and assessment

System leverage points analysis of the energy policies (Paper IV) is a policy design and assessment tool with a high applied value. Its application does not have to be connected to an advanced theoretical and conceptual research and can be used independently from theoretical research. For example, it can be used as guidelines for energy policies' systemic impact assessment. In the current context of increased political demand for a holistic approach for energy and climate policy-making, for inclusion of social justice components in the political agenda (e.g. European Green Deal), for increased level of critical thinking related to purely techno-optimist solutions, the tools like system leverage points analysis have a high potential of improving the quality of policy making by providing better understanding of the trade-offs associated with different policies. This thesis provides an example of how such tool can be applied.

8.3.2. Academic

The main academic novelty of this thesis is provision of a research design example for interdisciplinary research in sustainable energy system domain (Paper V). By clearly demonstrating how quantitative and qualitative approaches for sustainable energy system development can be combined, this thesis contributes to a research toolkit that can be of a high value for the further academic research and which can inspire further developments of interdisciplinary energy system studies.

Making the case of how to construct a sustainable energy system narratives is one of the main focuses of this thesis. It contributes to extending academic knowledge, especially in the social sciences domain, related to exploring what sustainable energy system is and what its sustainability assessment criteria could be.

When it comes to discussing a contribution to particular theories and concepts, this thesis provides a strong contribution to the energy justice field. This is particularly manifested in operationalizing energy justice pillars (i.e. recognition, distributional, procedural justice) for designing socially sustainable principles for energy access provision. Additionally, this thesis contributes to connecting energy justice discourse to the energy sufficiency discourse which has been addressed in the literature only to a minor extent. This discourse can inspire further research on alternative-to-growth energy system narratives as well as contribute to further development of social sustainability frameworks for sustainable energy systems design and assessment.

System dynamics tools applied in this thesis for both conceptual and qualitative analysis, contributes to the cases of how different system dynamics tools can be applied for conceptualizing and for actual planning of sustainable energy systems.

8.4. Limitations and further research

The limitations of this PhD thesis are provided below in connection to the main research results discussed in 9.2.

8.4.1. Limitations

(i) Limitations related to formulating the current energy paradigm

A limited number of energy models were reviewed in connection to the current energy paradigm. The conclusions about the strengths and weaknesses of the different modelling approaches in relation to the correspondence to the current energy paradigm were generalized as being applicable for all the models that use particular modelling methods. Analyzing a larger sample of energy models belonging to each of the modelling approaches would have added more strength to the validity of the derived arguments.

The list of questions formulated within the current energy paradigm was designed based on major research and political changes in relation to the sustainable development agenda that had an impact on the way the energy system was seen. However, this list cannot be absolutely unbiased and exhaustive and would benefit from a critical revision of the presented list of the questions.

(ii) Limitations related to the Steady State of Energy concept and the goal of energy sufficiency

In this thesis, the argumentation for the energy sufficiency being a universal energy system goal is limited from both biophysical and social sustainability perspectives. The argument on social desirability of a maximum limit of a sufficient amount of energy per capita is the one that especially needs to be elaborated further. Discussion of the concept of energy sufficiency would benefit from a deeper elaboration of the argument, e.g., its connection to the philosophy of sufficientarianism. The interregional dynamics between the Global North and the Global South, their interrelation in the context of reaching the goal of energy sufficiency, is addressed in this PhD thesis only superficially and thus needs to be explored further.

(iii) Limitations related to the system dynamics model integrating socially sustainable energy system narrative

The boundaries of the model developed in this thesis were strict and include electricity provision only and this issue was only explored in the context of the Global South. Including, for example, access to clean and modern cooking fuels and more regions inside the model structure could have provided deeper insights into the technological dimension as well as into the dynamics between the Global North and Global South in relation to the explored energy system narrative. From a modelling perspective, the model is only illustrative, it is not predictive and does not reproduce historical behavior. As a result, the absolute numerical output of the model is not realistic nor predictive as it is rooted in simplified and limited descriptions of the system. For example, the cost structure of the relevant energy technologies is designed in a very simplified manner. On the biophysical level, the model lacks the resource limits associated with the different types of energy resources as well as the GHG emissions associated with the different types of energy generation technologies. However these elements were not needed to fulfil the aim of the model and the analysis. As a result, many improvements are possible to enhance the model for example in the context of energy policy. For example there is a potential for exploring more combinations of the energy provisions technologies and enhance the representation of the cost structures behind different energy provision technologies. It also would be interesting to include additional factors such as subsidies or taxes that would better correspond to policies in the existing energy system.

8.4.2. Further research

Based on the results of this study, there are several main areas of further research that would interesting to pursue in the context of sustainable energy system development. Those include:

1) Further research on exploring interregional dynamics between the Global North and Global South, especially in the context of systems analysis. This could contribute to a better understanding of how sustainable energy system state can be achieved and what are the main trade-offs associated with this.
2) The designed sustainable energy system narrative could be developed further and be connected to the biophysical energy provision principles. This would allow for a stronger normative framework of sustainable energy provision and would contribute to a higher instrumental value of sustainable energy system narratives for a sustainable energy policy design and assessment.
3) Connecting the agendas of alternative-to-growth sustainable energy systems narratives to the alternative-to-growth sustainable economies research could be mutually beneficial for both these research domains. It could help identifying the gaps and inconsistencies of the designed visions and can drive new research questions. Sufficiency economy, degrowth, bioeconomy are examples of sustainable economic narratives that could be explored in the connection to sustainable energy system narratives. It would be especially interesting to explore alternative-to-growth economy and energy narratives on a global scale, particularly, to test possible implications of the energy sufficiency being a universal energy system goal for the Global North and the Global South.

8.5. Conclusion

This PhD thesis explores sustainable energy system on a global scale bringing together methods and tools that can help sustainable energy policy design and assessment. are the two main parts of this thesis.

A wide range of tools offered in this PhD thesis within the Energy system modelling and Sustainable energy system narratives parts can be used for sustainable energy policy design and assessment at different scales. This thesis has a high political relevance for decision-makers in a sustainable energy policy domain. The strength of the developed tools is their potential for universal application and for a customization depending on specific regional, political, technological, economic and social contexts.

Socially sustainable energy system framework developed in this PhD thesis based on the recognition, distributional and procedural justice principles provides an example of energy technologies assessment framework. This framework could be equally valuable for designing and assessing sustainable energy provision projects in developing countries that do not have access to a sufficient amount of energy services and for the energy transition project in the developed countries which have already developed energy systems and are currently looking for socially just solutions for carbon neutral energy transitions (e.g. European Green Deal).

The results of a conceptual analysis of a steady state of energy system as well as leverage points analysis of energy system policies could be very insightful for energy policy-making process helping prioritize and the policies with the highest systemic impact (i.e. re-thinking overall energy system goals, ensuring energy justice principles implementation in different world regions instead of being mainly focused on energy efficiency and clean technological solutions).

The results related to the energy system modelling part of this thesis could be insightful for developing new modelling techniques and re-considering modelling assumptions. By developing energy system models' structures around sustainability-oriented questions and by explicitly addressing social sustainability dimension in the modelling assumptions, energy modelling practice could help better informed energy policy-making process.

Apart from a direct policy-relevant applied value, the concepts developed in this PhD thesis are valuable for a broad sustainable energy policy discourse. Socially sustainable energy system narrative and, particularly, energy sufficiency as a universal energy system goal, are challenging the existing sustainable energy policy discourse. They are questioning fundamental energy system goals and are encouraging thinking outside of the techno-optimist and green-growth-oriented energy transition box. One of the best uses of the developed concepts would bringing them on a higher macroeconomic level and continue critically re-thinking sustainable energy system in connection to other economic sectors and to a broader socio-technical transitions towards sustainability.

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